PRODUCTIVE FACADES:
POTENTIAL ENERGY AND FOOD HARVESTING IN SINGAPORE'S RESIDENTIAL BUILDINGS

Renewable Resources and Architecture: M. 'Ammar Bin Mohamad Malek, Ng Zhi Li Sean, Wang Yigeng, Tay Lee Kuan Roy, 2015

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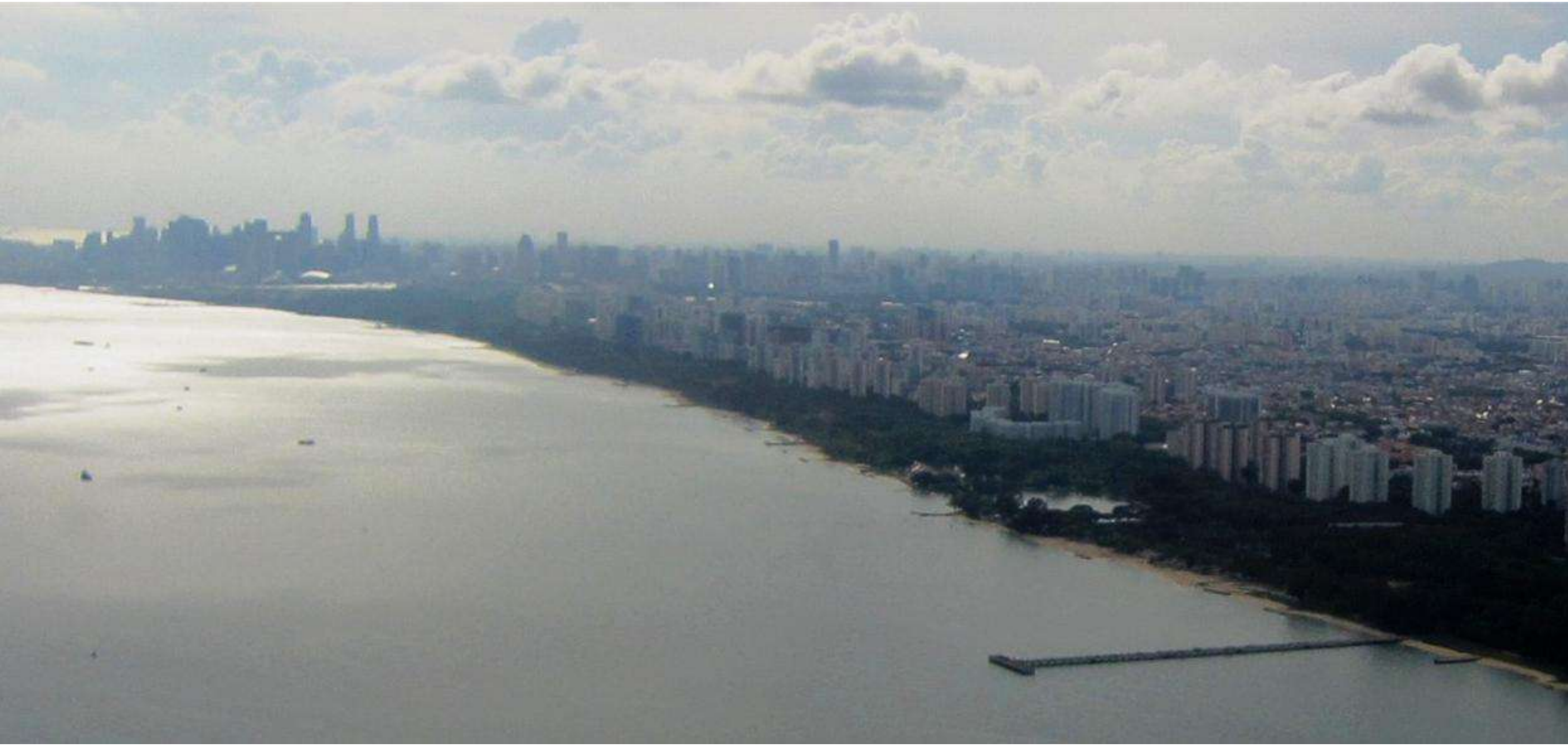
I. Background



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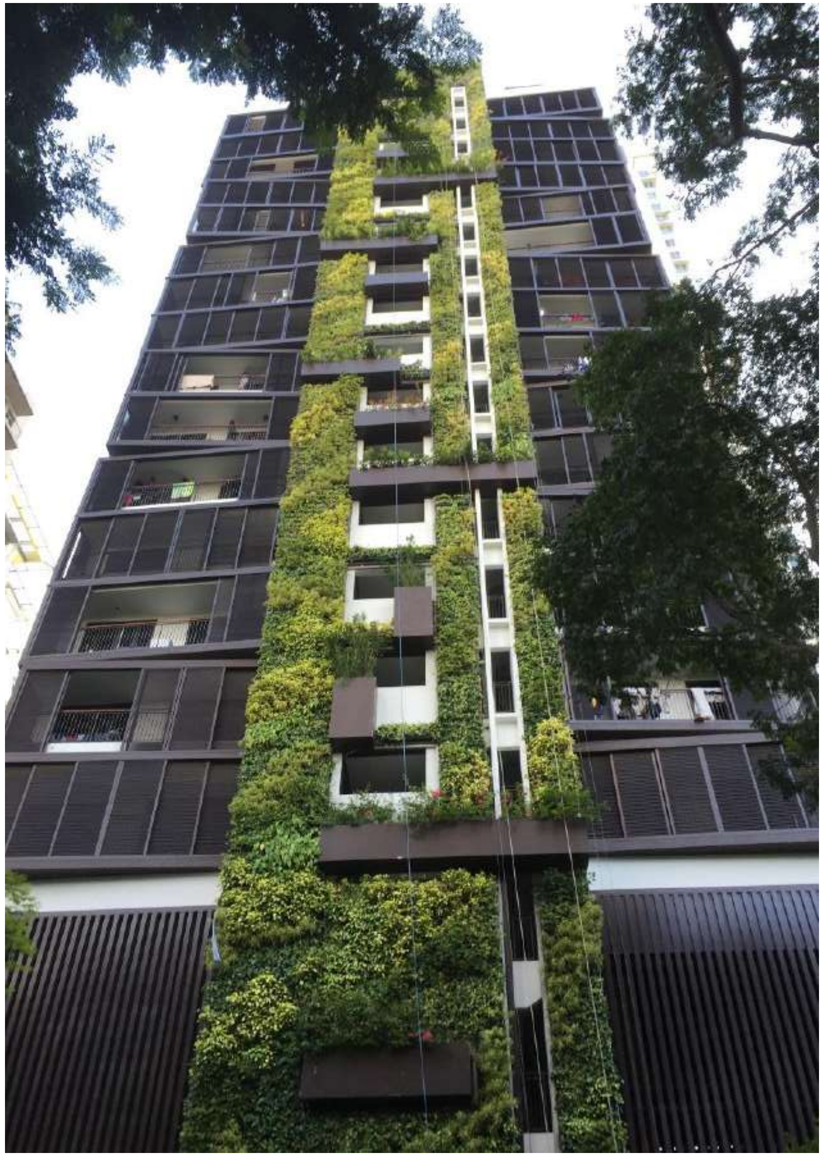

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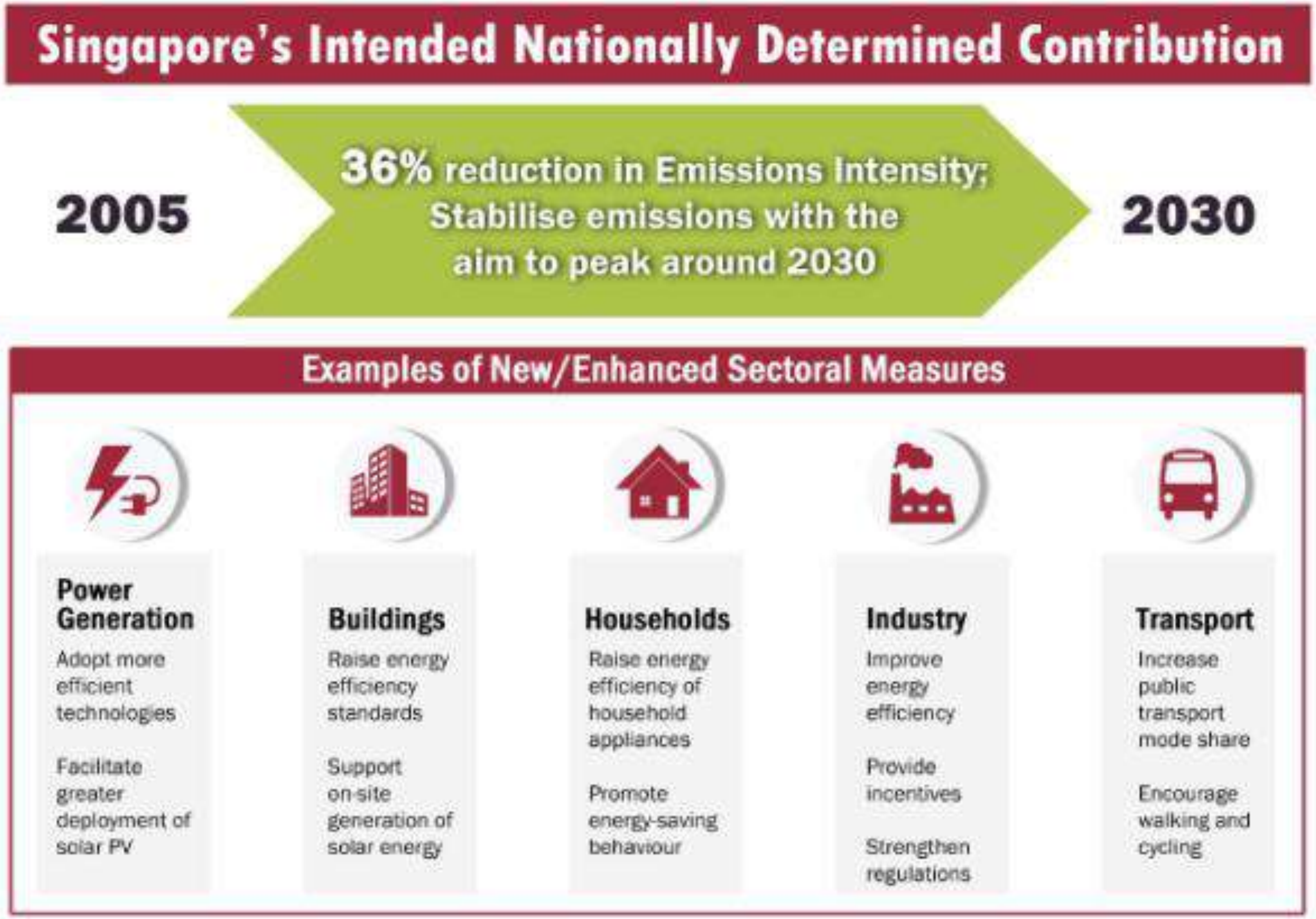

http://www.greenfuture.sg/2015/12/16/the-paris-agreement-what-it-means-for-singapore-and-what-more-can-we-do/

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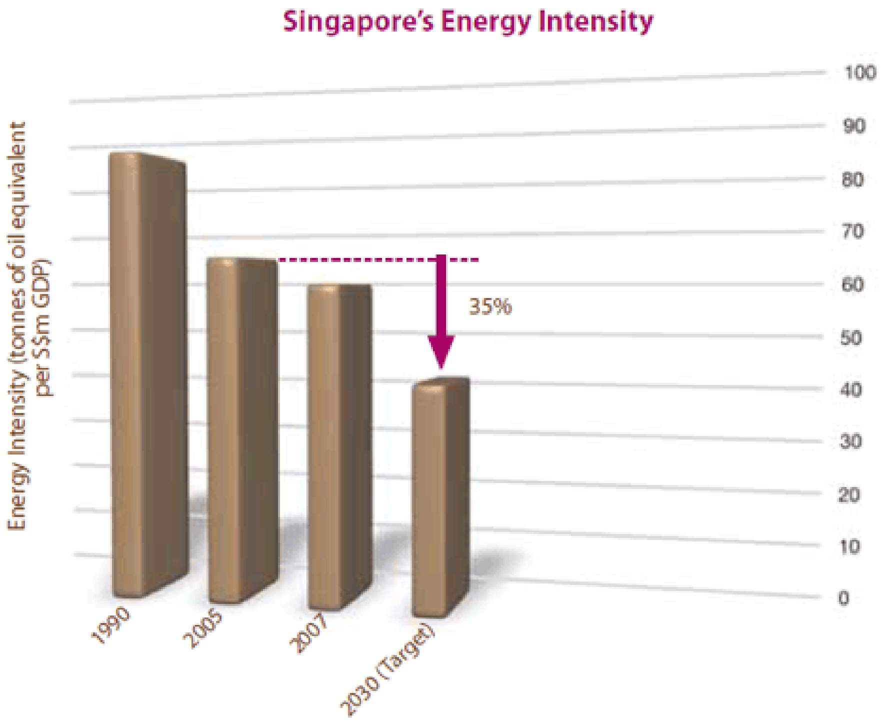
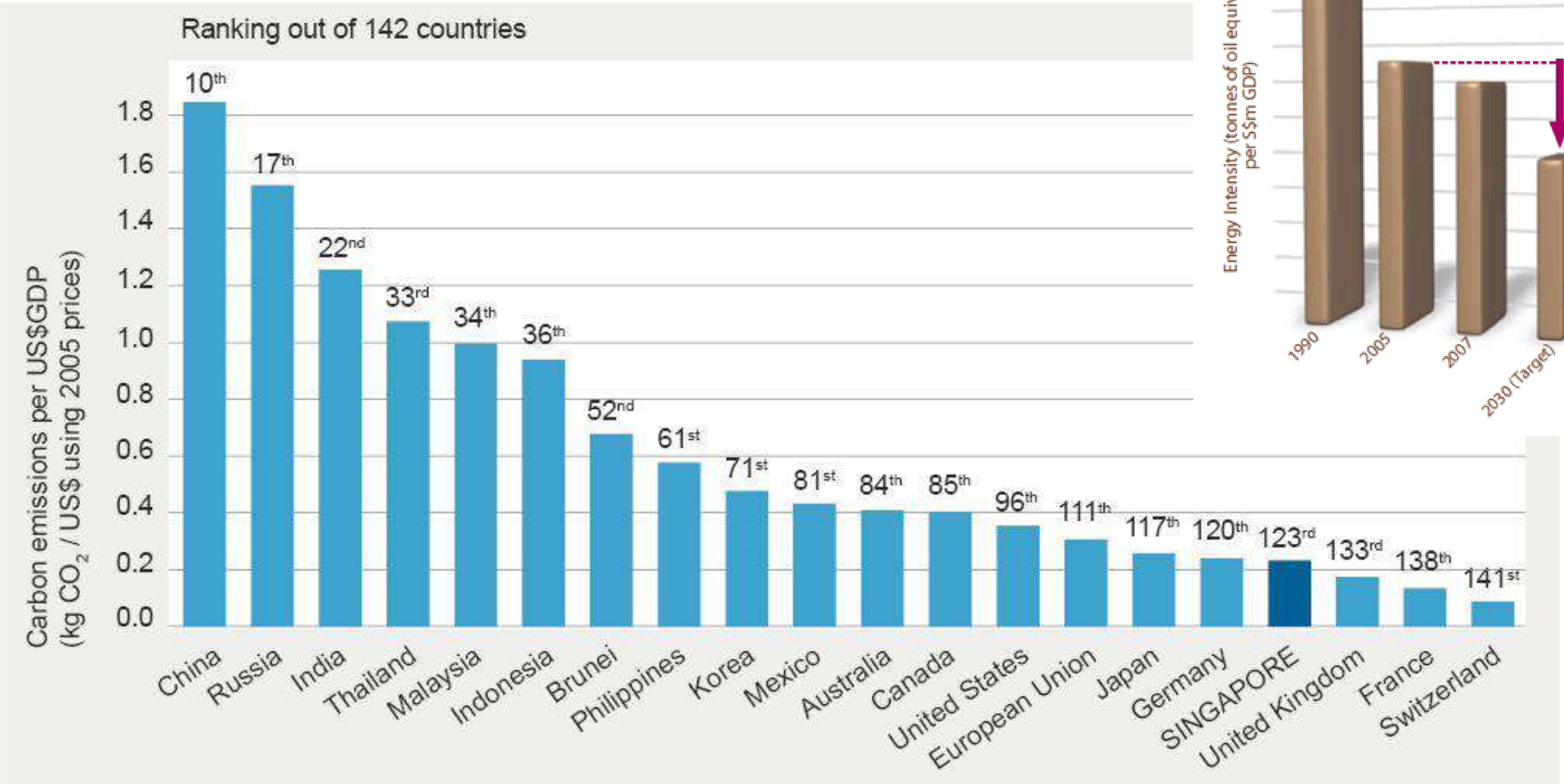
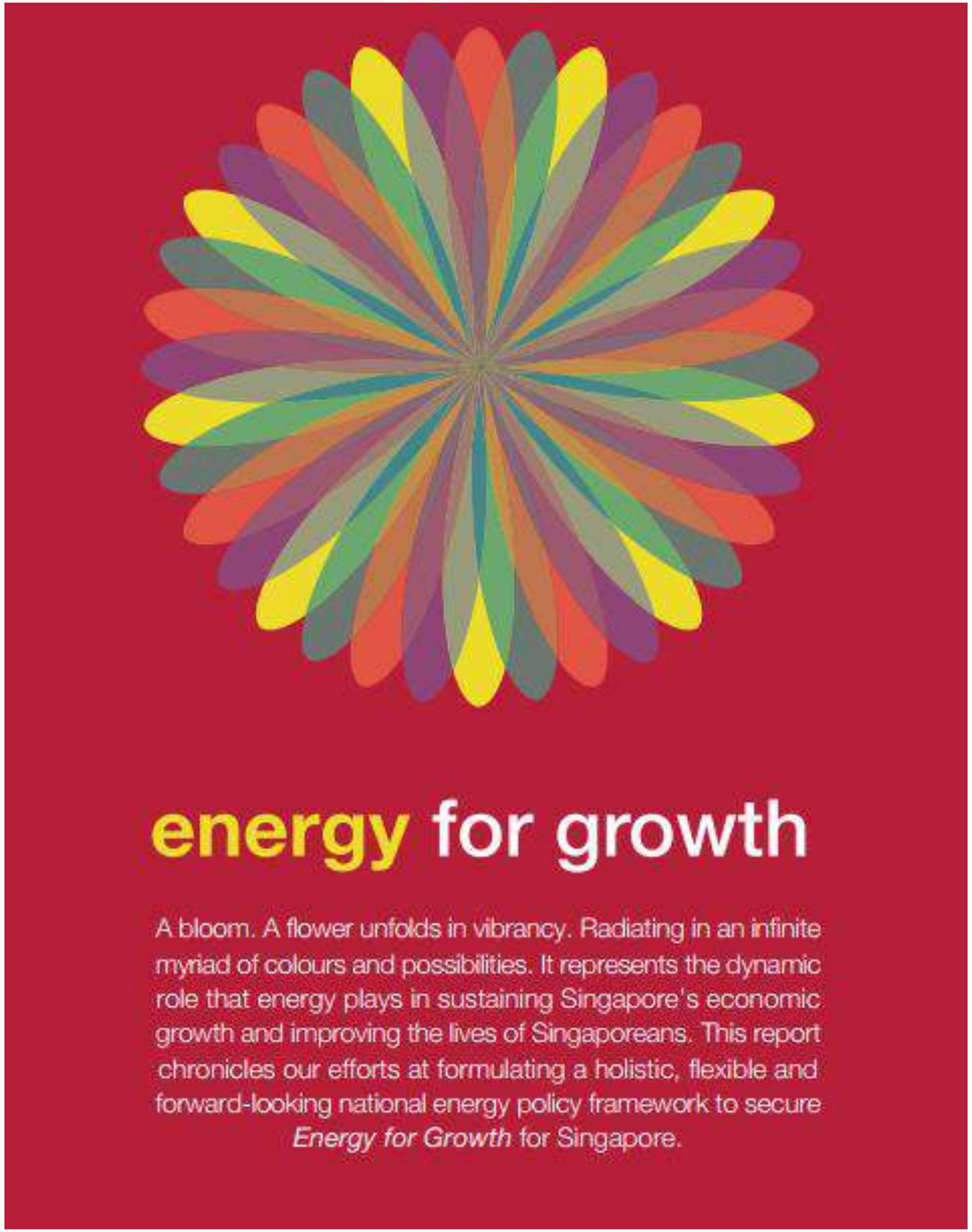




Source: CO_2 Emissions from Fuel Combustion - 2015 Highlights © OECD/International Energy Agency, 2015

https://www.mti.gov.sg/ResearchRoom/Documents/app.mti.gov.sg/data/pages/885/doc/NEPR%202007.pdf



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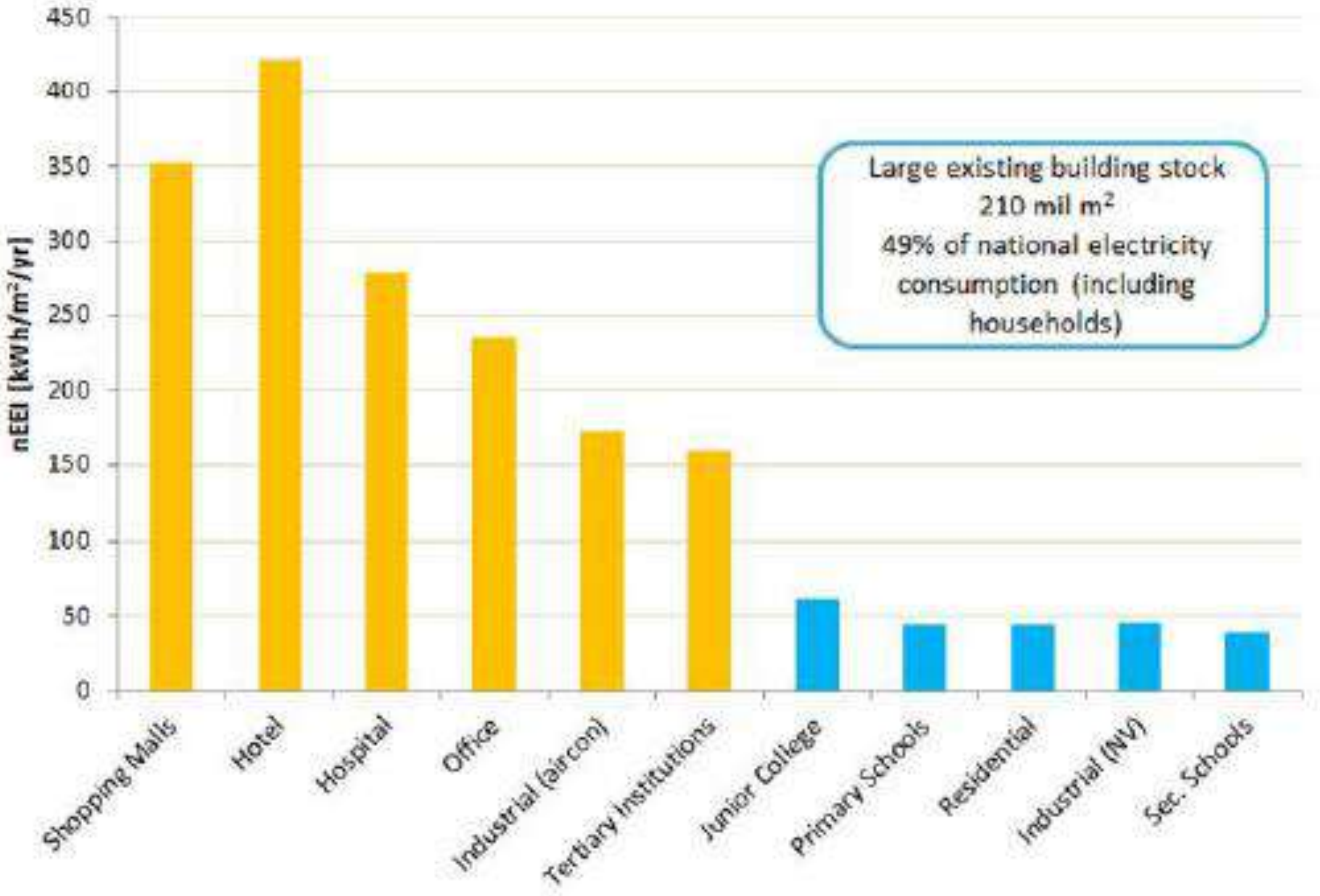

Figure 1.2: Energy consumption in existing building types (BCA, 2012a)

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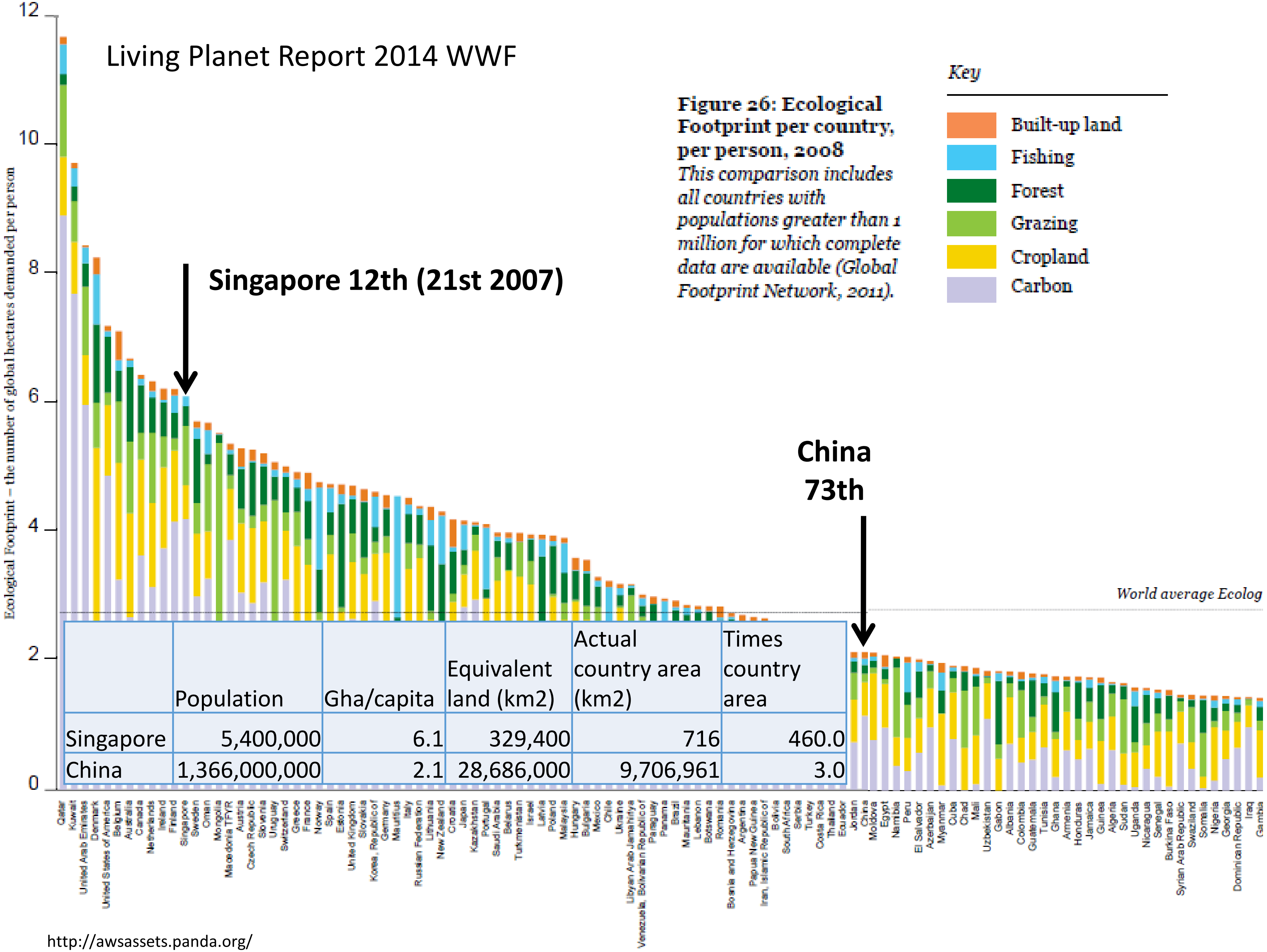
Living Planet Report 2014 WWF



	Population	Gha/capita	Equivalent land (km2)	Actual country area (km2)	Times country area
Singapore	5,400,000	6.1	329,400	716	460.0
China	1,366,000,000	2.1	28,686,000	9,706,961	3.0

http://awsassets.panda.org/

X SINGAPORE

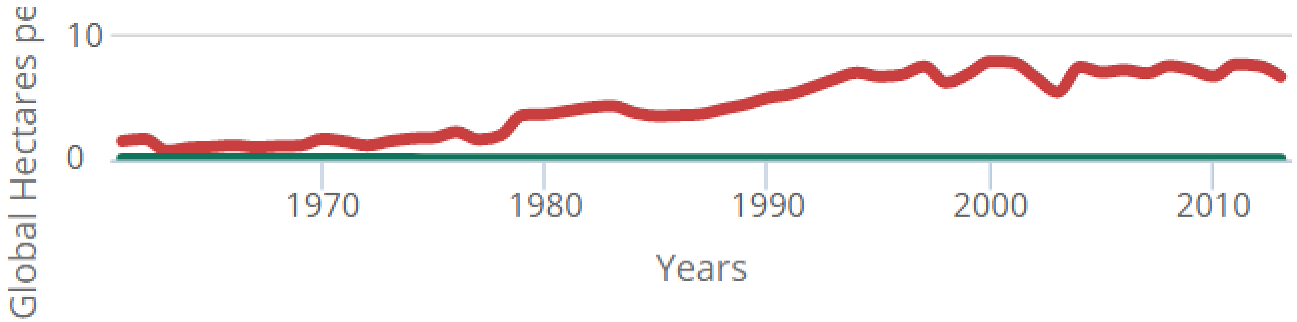
POPULATION (2013)
5,405,009

ECOLOGICAL FOOTPRINT PER CAPITA	BIOCAPACITY PER CAPITA	BIOCAPACITY CREDIT(+)/DEFICIT(-)
6.8 GHA	**0.1** GHA	**-6.7** GHA

ECOLOGICAL FOOTPRINT AND BIOCAPACITY FROM 1961 TO 2013

Ecological Footprint

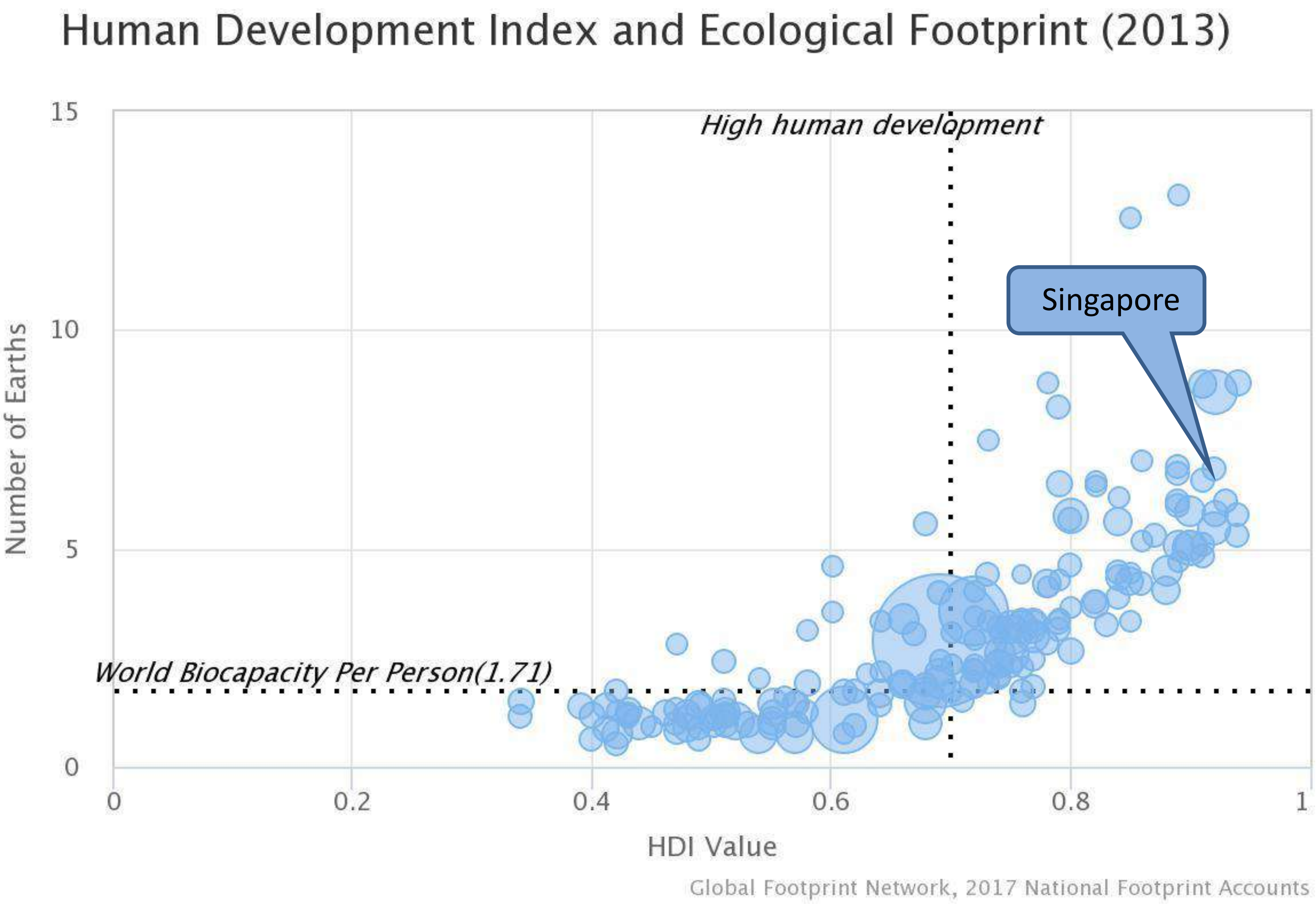
Biocapacity



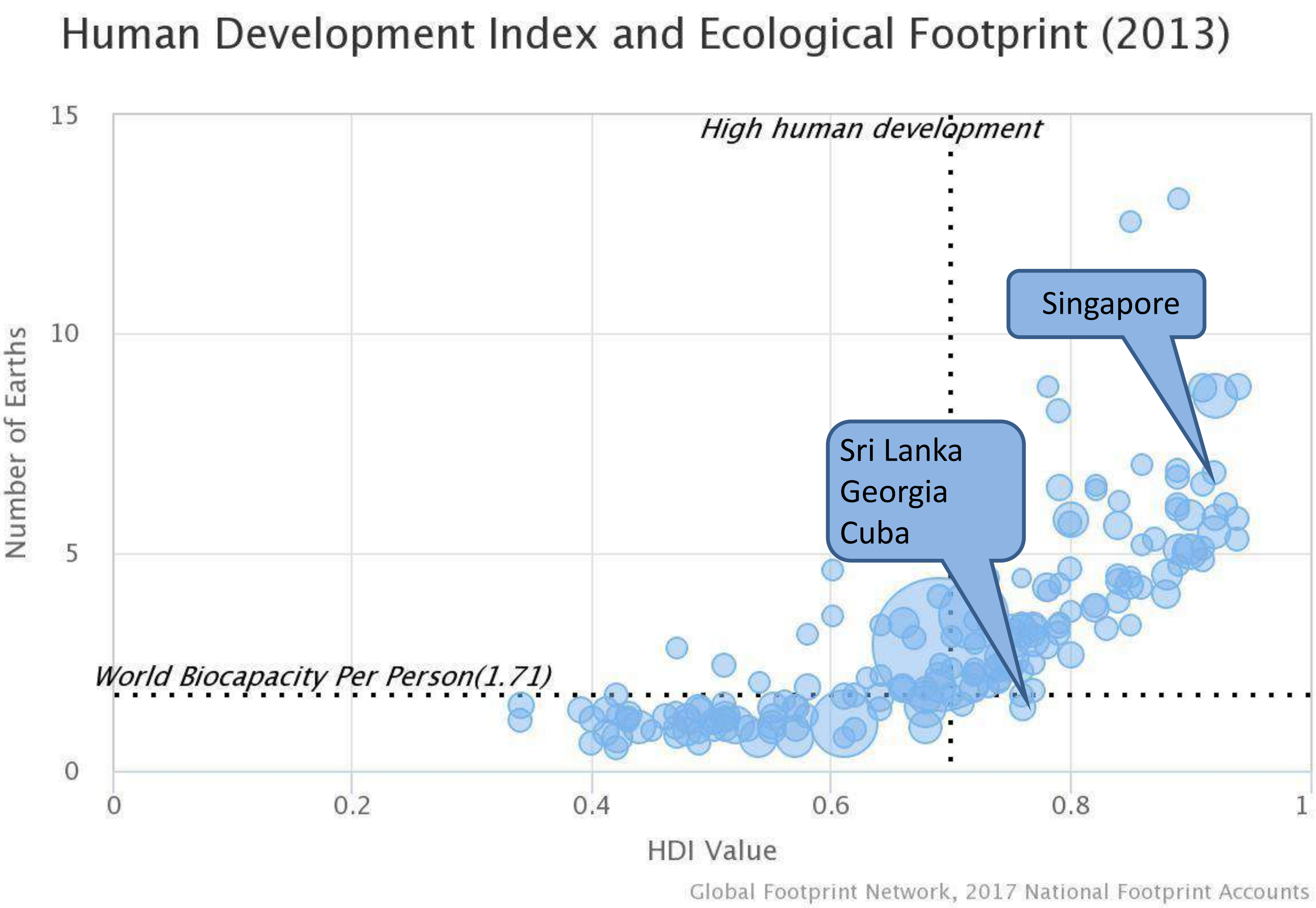
Data Sources: National Footprint Accounts 2017 (Data Year 2013); World Development Indicators, The World Bank (2016); U.N. Food and Agriculture Organization.
Learn More: Download and interact with data at data.footprintnetwork.org.

COUNTRIES RANKED BY ECOLOGICAL FOOTPRINT PER CAPITA (in global hectares)

Rank	Country	GHA	Rank	Country	GHA
1	Luxembourg	13.1	9	Estonia	7.0
2	Qatar	12.6	10	Belgium	6.9
3	Australia	8.8	11	Singapore	6.8
4	Trinidad and Tobago	8.8	12	Finland	6.7
5	Canada	8.8	13	Sweden	6.5
6	United States	8.6	14	Latvia	6.5
7	Kuwait	8.2	15	Kazakhstan	6.5
8	Mongolia	7.5	16	Bahrain	6.4



http://data.footprintnetwork.org/countryMetrics.html?cn=49&yr=



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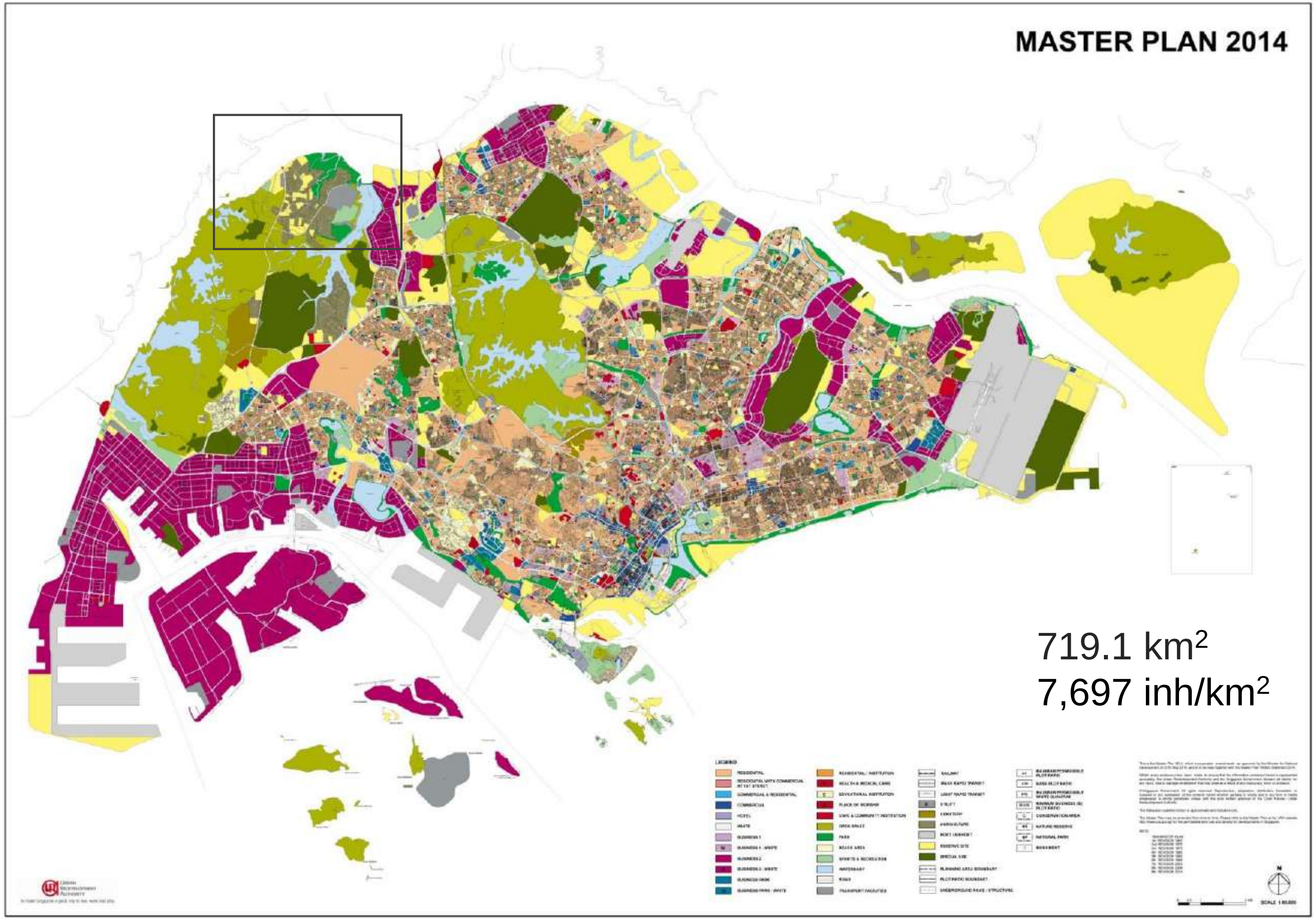


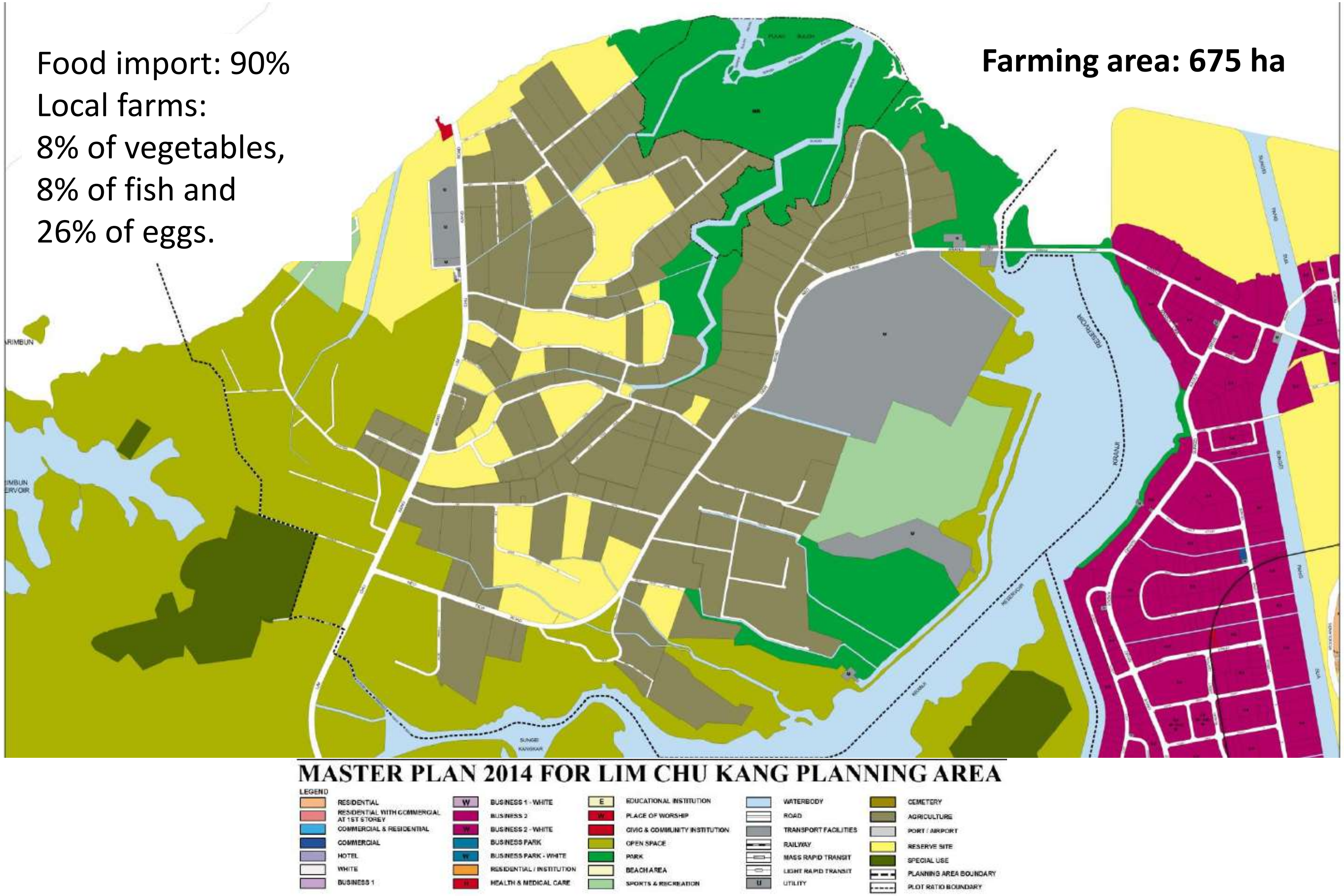
719.1 km^2

7,697 inh/km^2

I. Background

Food import: 90%
Local farms:
8% of vegetables,
8% of fish and
26% of eggs.

Farming area: 675 ha



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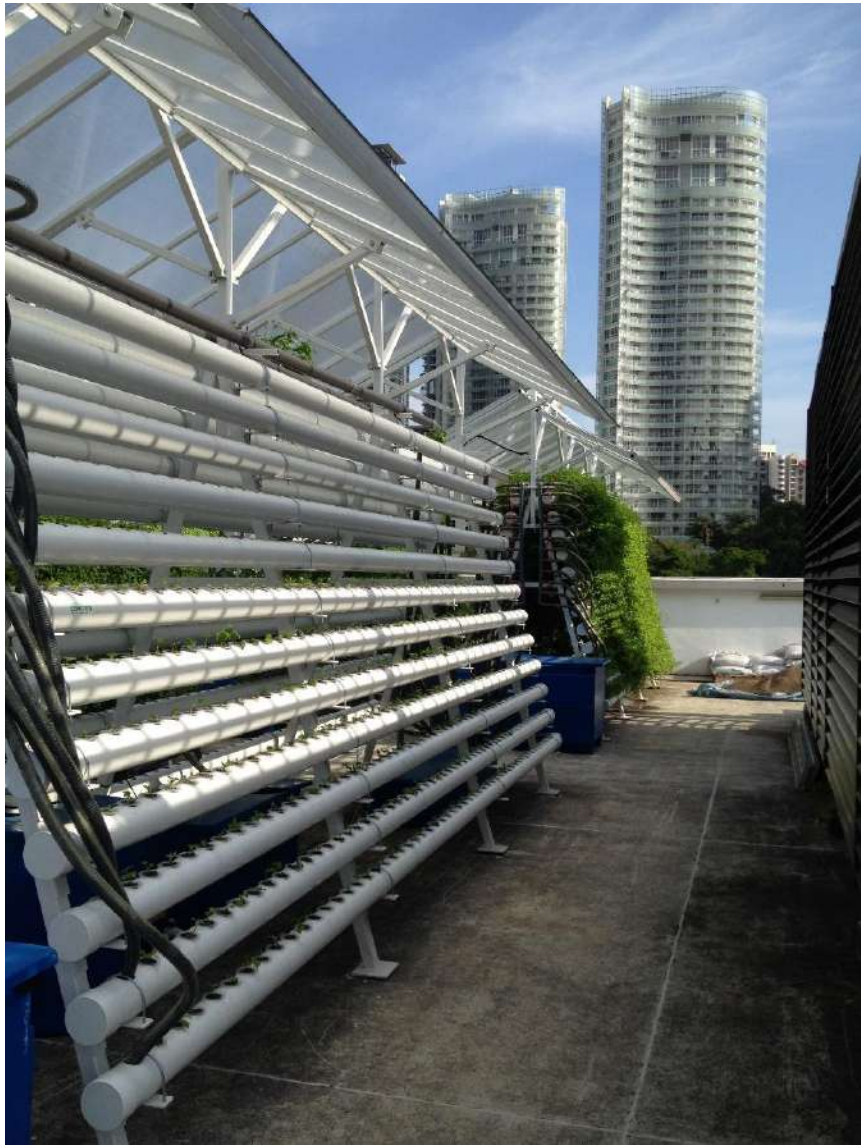

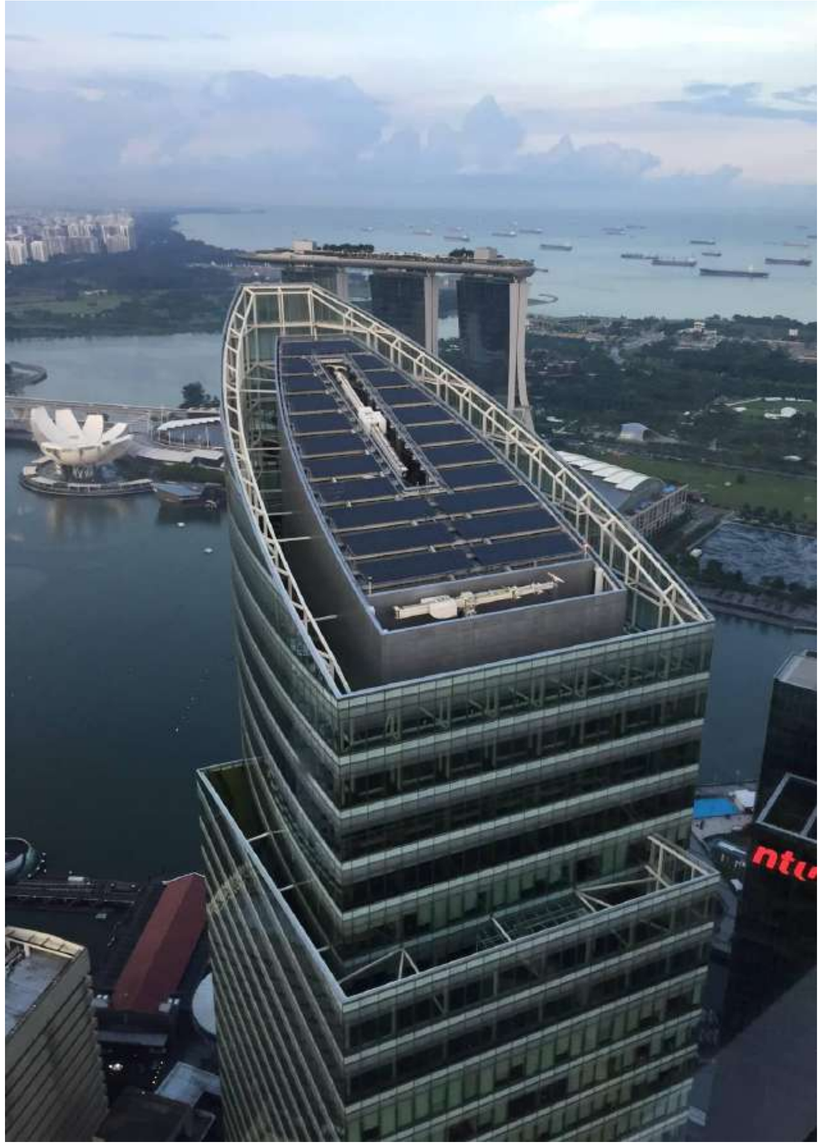

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Solar Energy 139 (2016) 757–769

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Sunlight availability and potential food and energy self-sufficiency in tropical generic residential districts

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A R T I C L E I N F O

Article history:
Received 17 May 2016
Received in revised form 23 August 2016
Accepted 22 October 2016
Available online 2 November 2016

Keywords:
Solar access
BIPV
Urban farming
Low-carbon neighbourhoods
Urban resilience

A B S T R A C T

A transition to a solar-based carbon neutral economy is crucial to reduce the overall ecological footprint and greenhouse gas (GHG) emissions while providing new housing for the growing urban population worldwide. One of the key measures to achieve such reductions as a way to mitigate and adapt to climate change is to increase food and energy self-sufficiency in residential areas. The objective of this study is to explore the potential self-sufficiency in terms of food and energy in generic residential districts in Singapore and Southeast Asia. Computational tools are employed to obtain quantifiable indicators based on sunlight availability. A series of building typologies and urban forms was created as abstractions from actual residential developments in Singapore (1.3°N). In total, 57 cases were assessed in terms of sunlight availability and the impact of three density and geometry parameters: plot ratio, site coverage and building height were considered. Results from selected cases were compared to Hanoi's conditions (21°N).

The results show that the indicators having the higher impact on the food and energy self-sufficiency are plot ratio and building height. The cases with the lowest plot ratio (PR < 1.9) achieved food self-sufficiency when a hybrid higher-yield farming method was applied. Regarding energy harvesting, the cases with the lowest building height (<42 m) achieve energy self-sufficiency due to the maximum exposed area with PV per number of residents. In low-latitude regions, solar access is more evenly distributed among all facade orientations than in higher latitudes, therefore providing all facade orientations with food and energy harvesting potential. Food and energy self-sufficiency in equatorial regions is more heavily influenced by the available farming and PV area in relation to the total population than by the reduction of sunlight availability due to building typology and morphology.

1. Introduction

According to UN Habitat, new housing should be provided for 2.25 billion people by 2030 (UN-Habitat, 2012). This includes the 1.43 billion people expected to migrate to urban areas and those living in precarious conditions who will need decent and affordable houses. A large percentage of this amount corresponds to tropical and subtropical regions. Only by an urgent but well-planned transition from fossil fuels to a solar-based carbon neutral economy can these huge challenges be surmounted while reducing the overall ecological footprint and greenhouse gas (GHG) emissions.

The urbanisation process is accelerating along the tropical belt, especially in Southeast Asia (SEA). In Singapore, although all the population is already urbanised, the need to build higher density residential districts to accommodate the growing population in the land-scarce Estate-Island obliges the demolition of relatively old housing estates and the construction of new ones. In other tropical and subtropical regions, the land used to build new residential districts is, most of the time, located in the peri-urban areas in which agricultural activities are foremost. This poses tremendous stress on food production and food availability. On the one hand, food demand is increased due to the growing population with higher income level and, on the other hand, fertile land around the cities is dramatically reduced. In the case of Singapore, new residential developments have already reduced the farming areas considerably, which has increased its food dependency and compromised future food security.

It is estimated that the yield increase rate of the main crops will not be sufficient to cope with the growing demand by 2050 due to the increase of population, the dietary shift towards meat and dairy, especially in Asia, and biofuel consumption (Tilman et al., 2011; Ray et al., 2013). In addition, the increase of land for agriculture to cope with the growing demand could directly affect natural ecosystems like tropical forests. Therefore, using building

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http://dx.doi.org/10.1016/j.solener.2016.10.041

Impact of urban form on sunlight availability for urban farming in Asian cities at different latitudes

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POTENTIAL USE OF BUILDING FACADES FOR FOOD AND ENERGY HARVESTING IN SINGAPORE

Abel Tablada and Shashwat

Department of Architecture
National University of Singapore (NUS)

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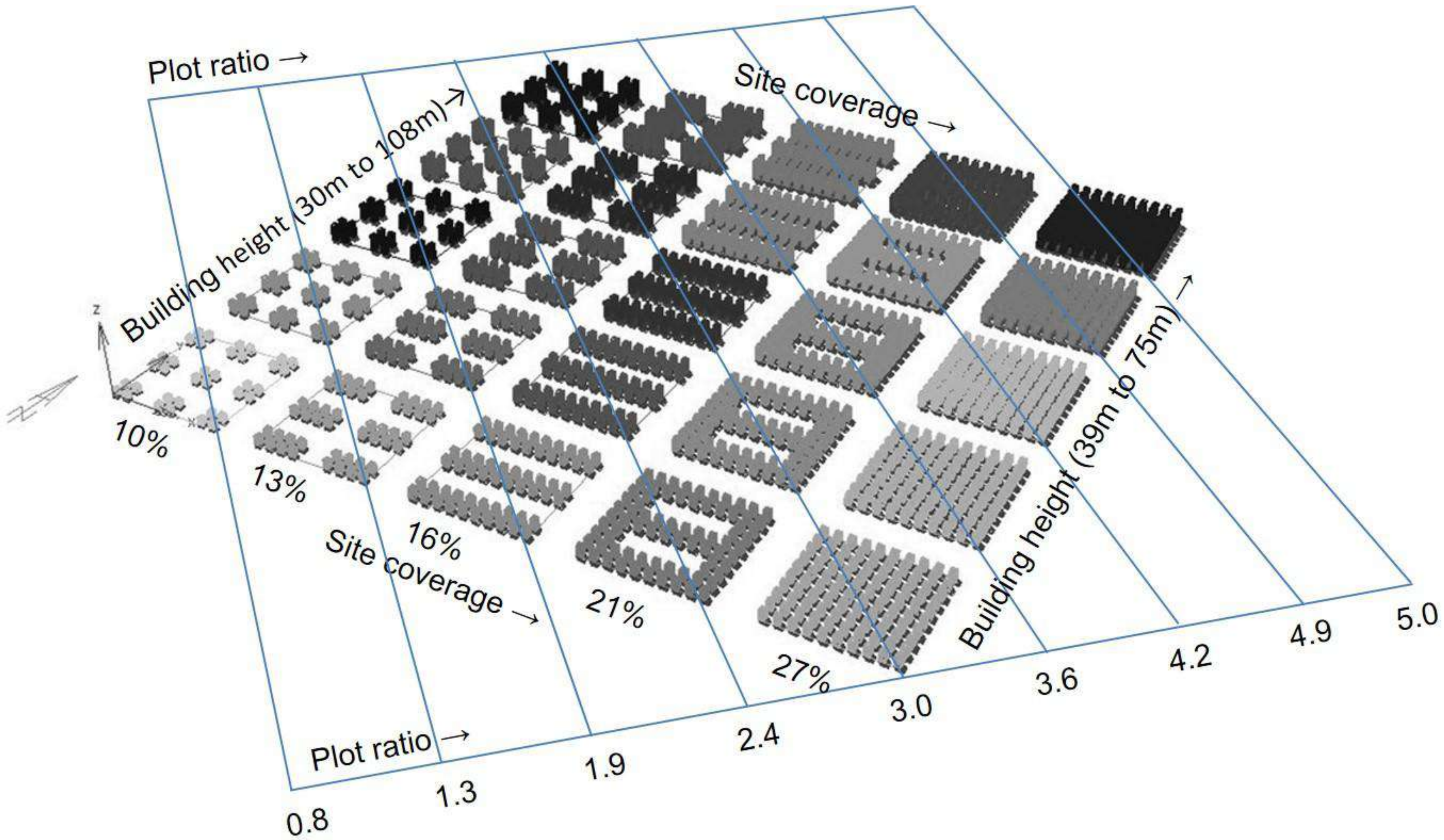
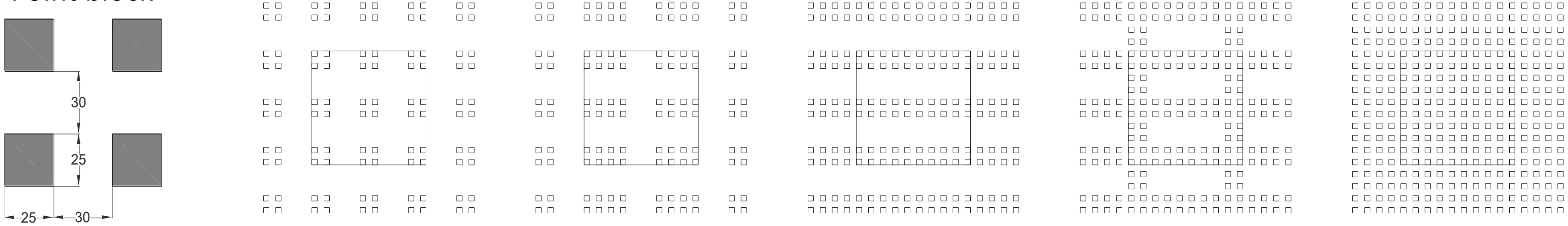
II. Productivity potential at urban level

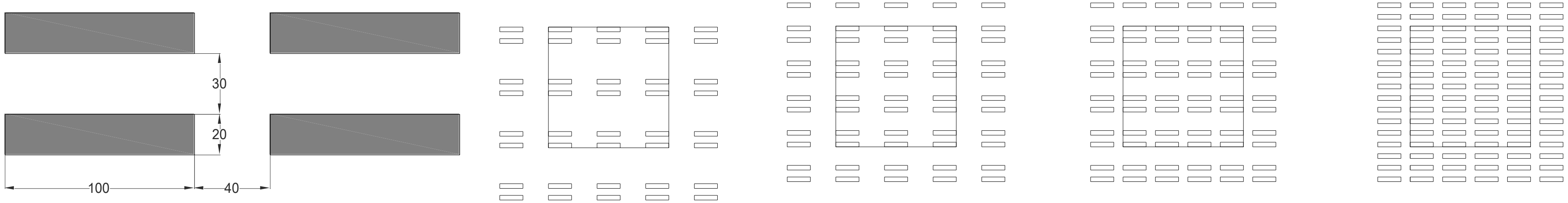


II. Productivity potential at urban level

Point block

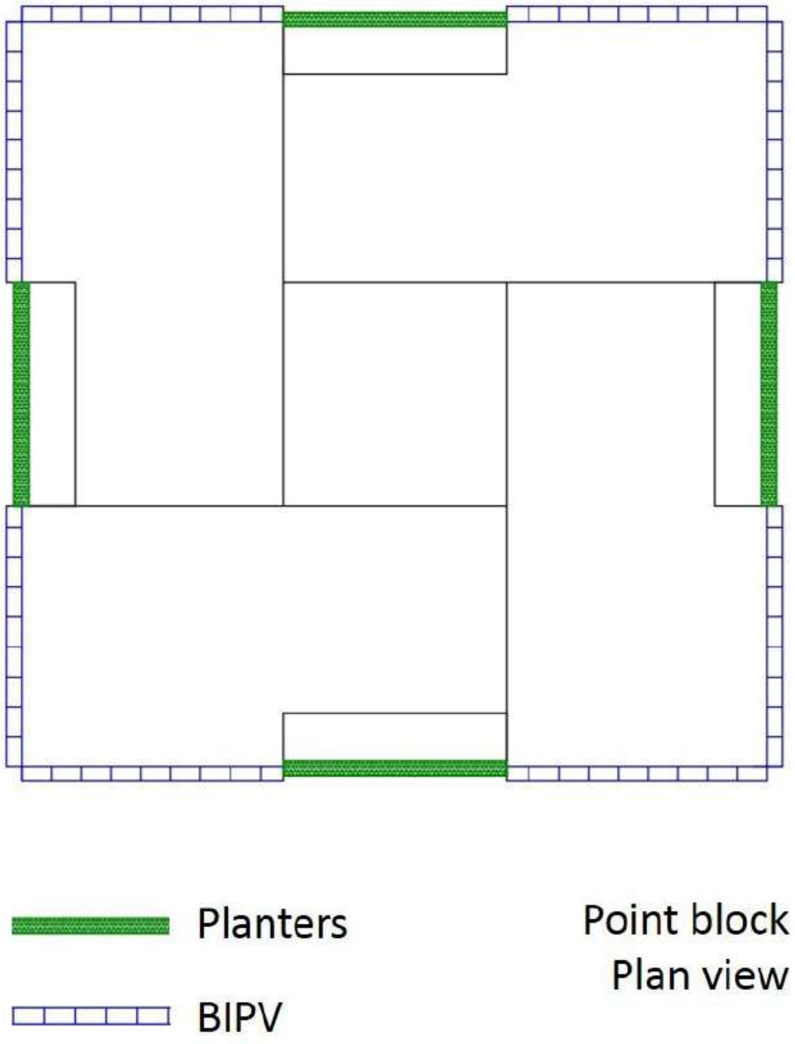


Slab block



Contemporary block

II. Productivity potential at urban level



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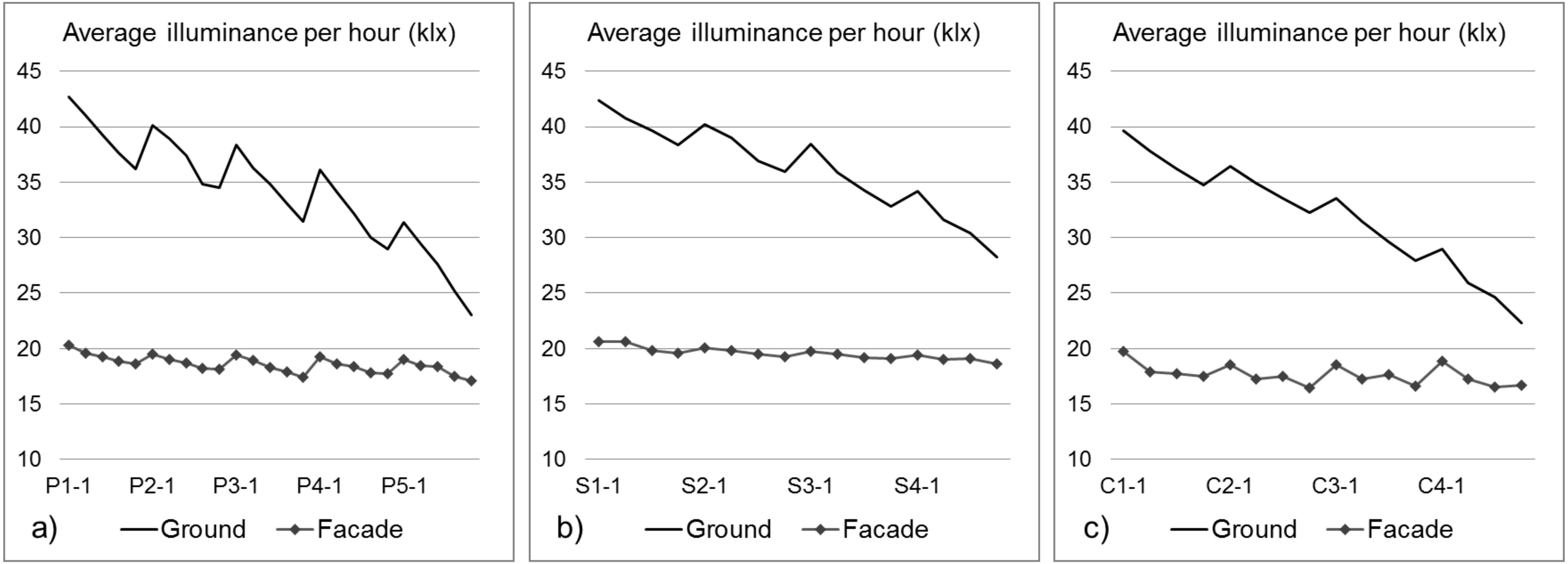

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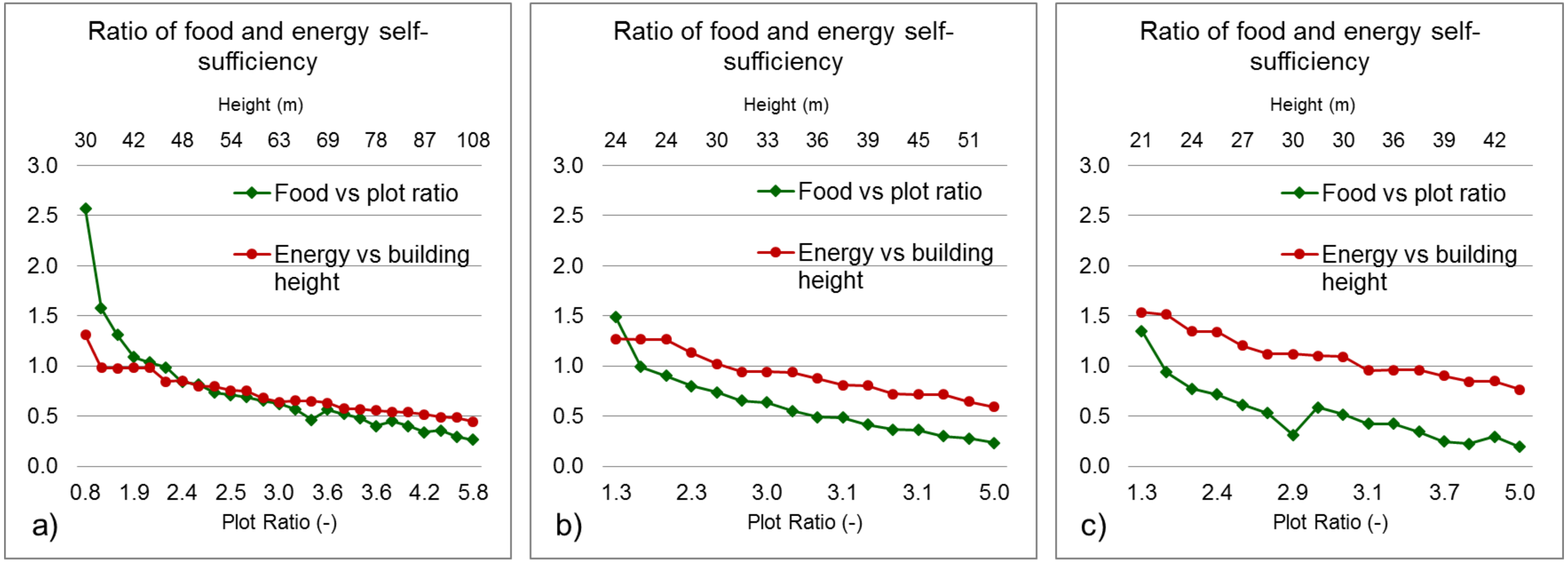

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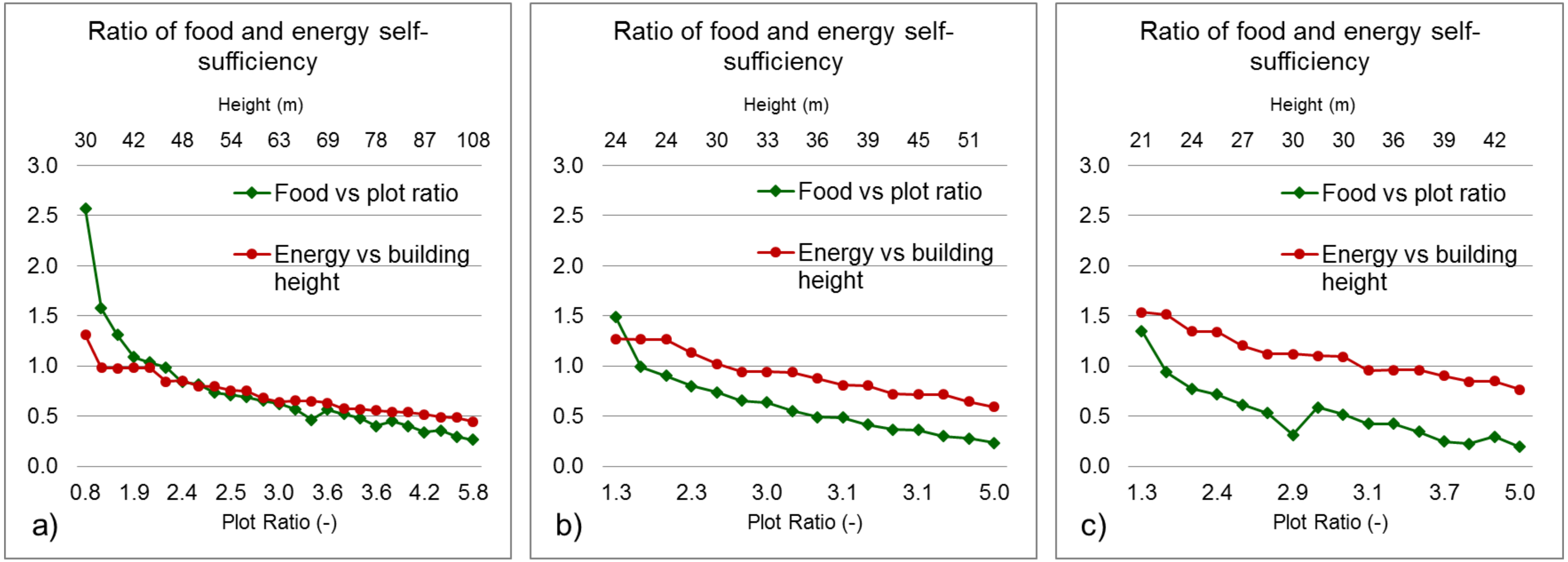

- Food self-sufficiency is achieved with PR ≤ 1.9 if a hybrid farming method is applied (conventional + vertical).
- Energy self-sufficiency is achieved for building height (< 42 m, < 14 storeys, PR < 3) due to the maximum exposed area with PV per amount of residents.

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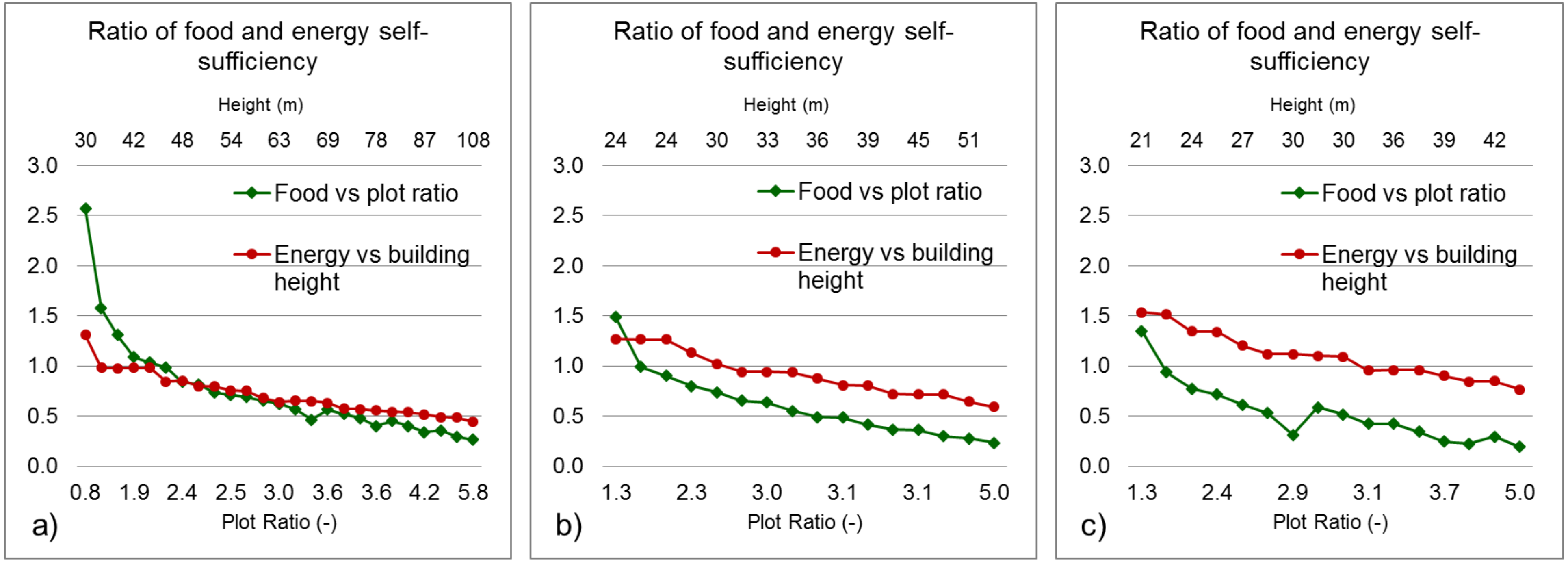

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- Energy self-sufficiency is achieved for building height (< 42 m, < 14 storeys, PR < 3) due to the maximum exposed area with PV per amount of residents.
- Sunlight availability is sufficient for food and energy harvesting on all façade orientations.
- For current typical New Towns in Singapore, food and energy self-sufficiency could reach about 60% and 80% respectively.

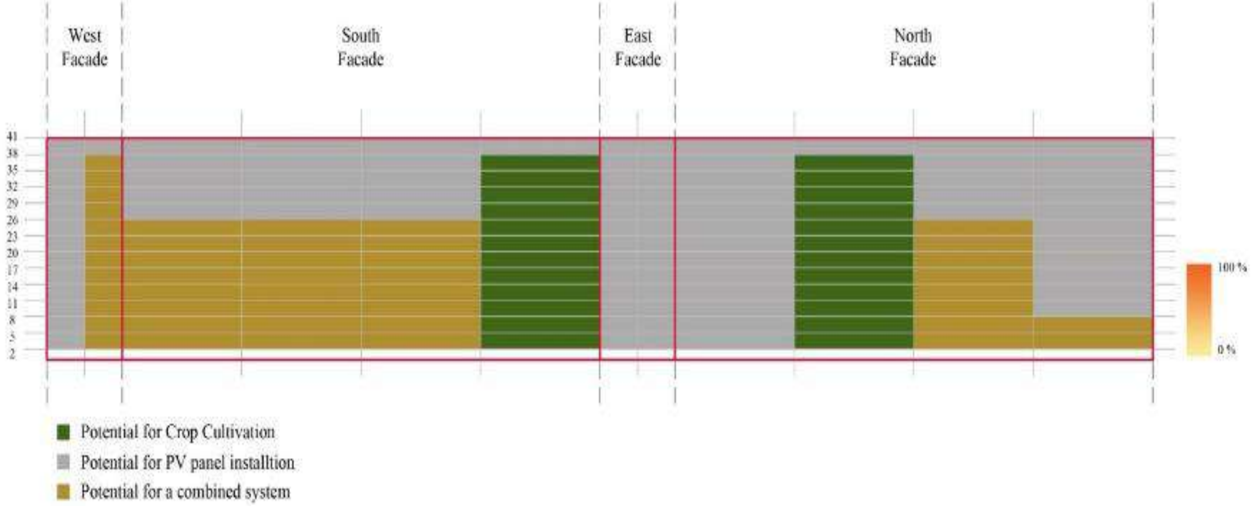
II. Productivity potential at urban level

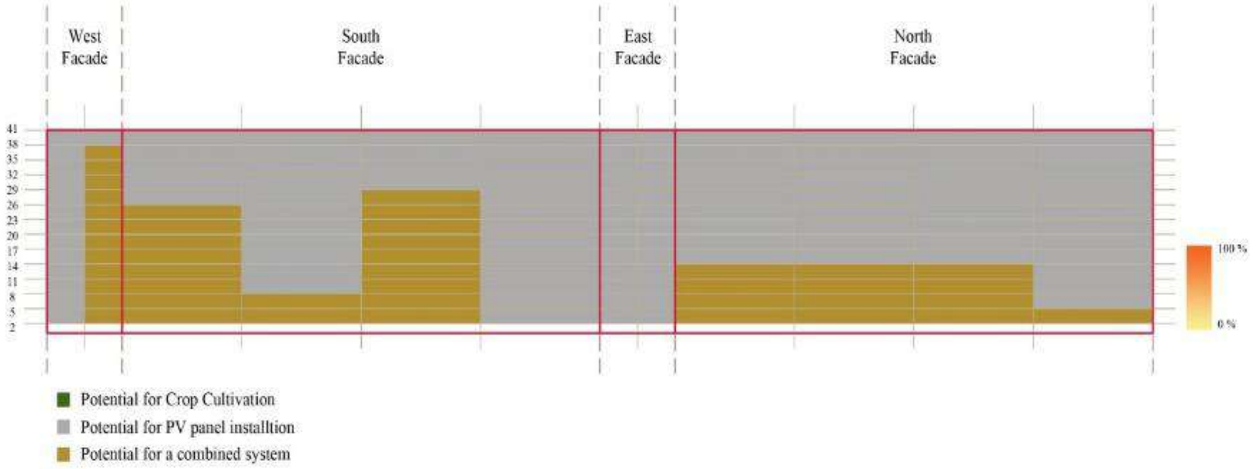
To make recommendations for three categories of envelope use based on facade sunlight distribution:

1) only BIPV,

(2) combination of BIPV and farming

(3) only farming or solar collectors.





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1	515	54	71	1E+08	0.613	385	515	54	71	1E+08	0.618	440	515	54	71	1E+08	0.622	495	515	54	66	9E+07	0.542
2	507.5	54	71	1E+08	0.616	385	507.5	54	71	1E+08	0.616	440	507.5	54	71	1E+08	0.622	495	507.5	54	65	9E+07	0.536
3	500	54	71	1E+08	0.613	385	500	54	71	1E+08	0.619	440	500	54	71	1E+08	0.622	495	500	54	65	9E+07	0.541
4	515	42	68	9E+07	0.558	385	515	42	69	9E+07	0.565	440	515	42	69	9E+07	0.568	495	515	42	62	8E+07	0.488
5	507.5	42	68	9E+07	0.552	385	507.5	42	68	9E+07	0.555	440	507.5	42	68	9E+07	0.559	495	507.5	42	62	8E+07	0.478
6	500	42	68	9E+07	0.557	385	500	42	68	9E+07	0.56	440	500	42	68	9E+07	0.559	495	500	42	62	8E+07	0.484
7	515	30	65	8E+07	0.498	385	515	30	65	8E+07	0.502	440	515	30	65	8E+07	0.502	495	515	30	59	7E+07	0.422
8	507.5	30	65	8E+07	0.493	385	507.5	30	65	8E+07	0.493	440	507.5	30	65	8E+07	0.497	495	507.5	30	59	7E+07	0.425
9	500	30	65	8E+07	0.5	385	500	30	65	8E+07	0.498	440	500	30	65	8E+07	0.499	495	500	30	59	7E+07	0.425
10	515	18	63	8E+07	0.454	385	515	18	62	7E+07	0.452	440	515	18	63	7E+07	0.453	495	515	18	56	6E+07	0.377
11	507.5	18	61	7E+07	0.44	385	507.5	18	62	7E+07	0.445	440	507.5	18	62	7E+07	0.446	495	507.5	18	55	6E+07	0.373
12	500	18	62	7E+07	0.445	385	500	18	62	7E+07	0.447	440	500	18	63	7E+07	0.451	495	500	18	55	6E+07	0.375
13	515	6	59	7E+07	0.408	385	515	6	59	7E+07	0.407	440	515	6	59	7E+07	0.408	495	515	6	50	5E+07	0.331
14	507.5	6	58	7E+07	0.401	385	507.5	6	59	7E+07	0.405	440	507.5	6	59	7E+07	0.405	495	507.5	6	48	5E+07	0.323
15	500	6	59	7E+07	0.406	385	500	6	59	7E+07	0.409	440	500	6	59	7E+07	0.405	495	500	6	51	6E+07	0.336
16					0						0						0						0
17	460	54	71	1E+08	0.612	385	460	54	71	1E+08	0.617	440	460	54	72	1E+08	0.623	495	460	54	65	9E+07	0.539
18	452.5	54	71	1E+08	0.613	385	452.5	54	71	1E+08	0.614	440	452.5	54	71	1E+08	0.621	495	452.5	54	65	9E+07	0.535
19	445	54	71	1E+08	0.613	385	445	54	71	1E+08	0.617	440	445	54	71	1E+08	0.621	495	445	54	65	9E+07	0.54
20	460	42	68	9E+07	0.557	385	460	42	68	9E+07	0.563	440	460	42	69	9E+07	0.568	495	460	42	62	8E+07	0.486
21	452.5	42	68	9E+07	0.551	385	452.5	42	68	9E+07	0.551	440	452.5	42	68	9E+07	0.554	495	452.5	42	62	8E+07	0.479
22	445	42	68	9E+07	0.556	385	445	42	68	9E+07	0.559	440	445	42	69	9E+07	0.565	495	445	42	62	8E+07	0.482
23	460	30	65	8E+07	0.501	385	460	30	65	8E+07	0.503	440	460	30	65	8E+07	0.502	495	460	30	59	7E+07	0.428
24	452.5	30	64	8E+07	0.49	385	452.5	30	65	8E+07	0.498	440	452.5	30	65	8E+07	0.494	495	452.5	30	58	7E+07	0.418
25	445	30	65	8E+07	0.495	385	445	30	65	8E+07	0.5	440	445	30	65	8E+07	0.5	495	445	30	59	7E+07	0.424
26	460	18	62	7E+07	0.451	385	460	18	63	8E+07	0.455	440	460	18	63	8E+07	0.453	495	460	18	56	6E+07	0.377
27	452.5	18	62	7E+07	0.443	385	452.5	18	61	7E+07	0.442	440	452.5	18	61	7E+07	0.441	495	452.5	18	55	6E+07	0.368
28	445	18	62	7E+07	0.447	385	445	18	62	7E+07	0.448	440	445	18	63	8E+07	0.454	495	445	18	56	6E+07	0.375
29	460	6	59	7E+07	0.407	385	460	6	59	7E+07	0.406	440	460	6	59	7E+07	0.41	495	460	6	50	5E+07	0.331
30	452.5	6	58	7E+07	0.396	385	452.5	6	58	7E+07	0.4	440	452.5	6	59	7E+07	0.404	495	452.5	6	49	5E+07	0.328
31	445	6	59	7E+07	0.407	385	445	6	59	7E+07	0.41	440	445	6	59	7E+07	0.409	495	445	6	50	6E+07	0.334
32					0						0						0						0
33	405	54	71	1E+08	0.616	385	405	54	71	1E+08	0.62	440	405	54	71	1E+08	0.621	495	405	54	65	9E+07	0.535
34	397.5	54	71	1E+08	0.611	385	397.5	54	71	1E+08	0.615	440	397.5	54	71	1E+08	0.621	495	397.5	54	65	9E+07	0.539
35	390	54	71	1E+08	0.612	385	390	54	71	1E+08	0.617	440	390	54	71	1E+08	0.623	495	390	54	65	9E+07	0.54
36	405	42	68	9E+07	0.559	385	405	42	68	9E+07	0.564	440	405	42	68	9E+07	0.564	495	405	42	62	8E+07	0.484
37	397.5	42	68	9E+07	0.552	385	397.5	42	68	9E+07	0.553	440	397.5	42	68	9E+07	0.557	495	397.5	42	62	8E+07	0.479

II. Productivity potential at urban level

- Food thresholds

Daylight Autonomy (DA)

required sunlight (RS)

Optimal RS = 80% > 10klx

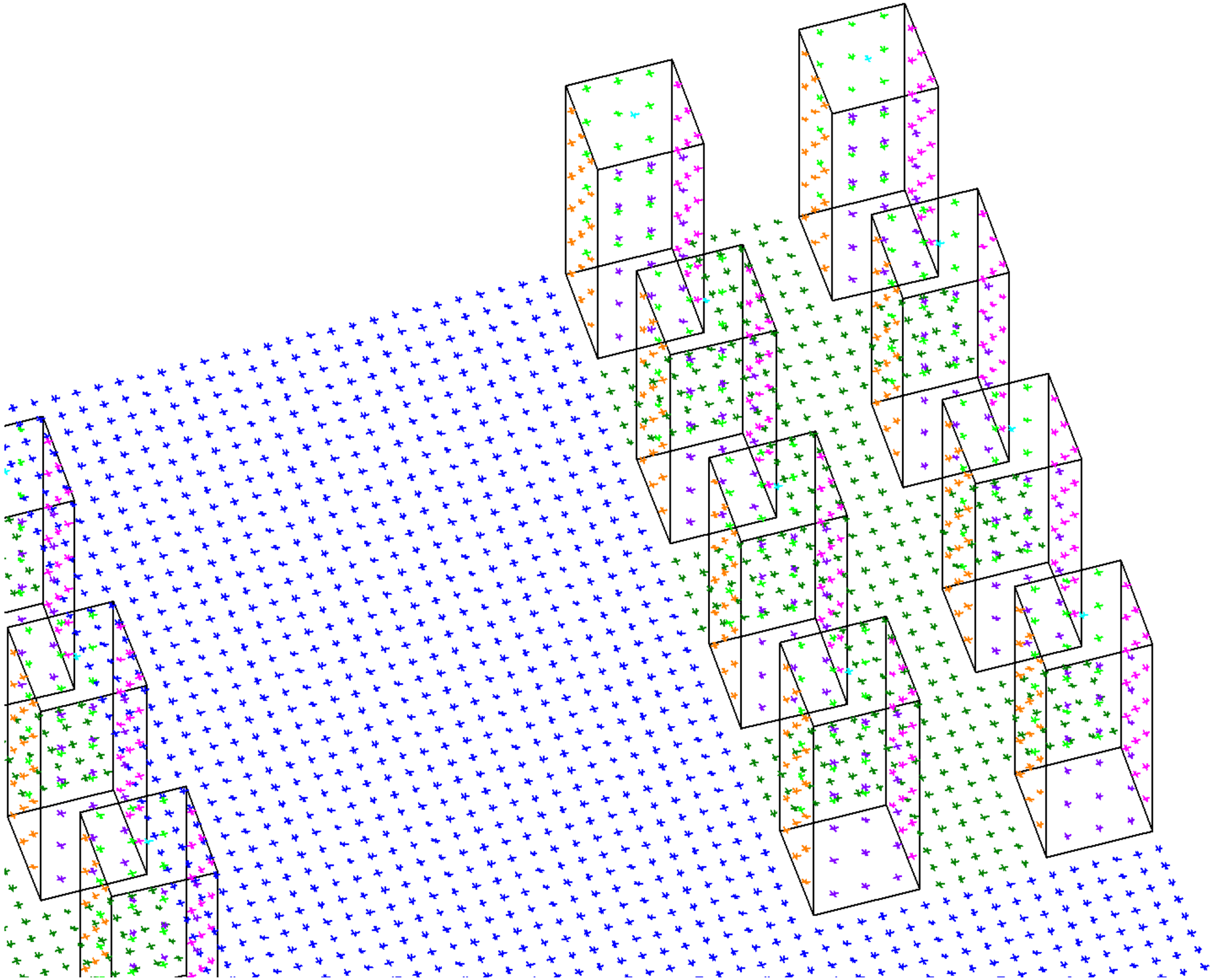
Minimum RS = 40% > 10klx

- Energy thresholds

Incident irradiance

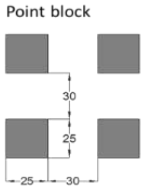
PV > 800 kWh/m²

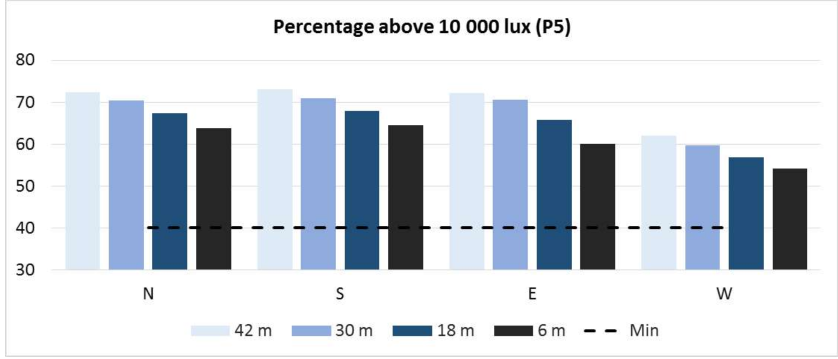
Solar collector > 400 kWh/m²

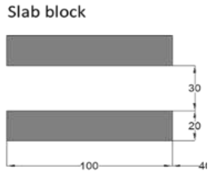


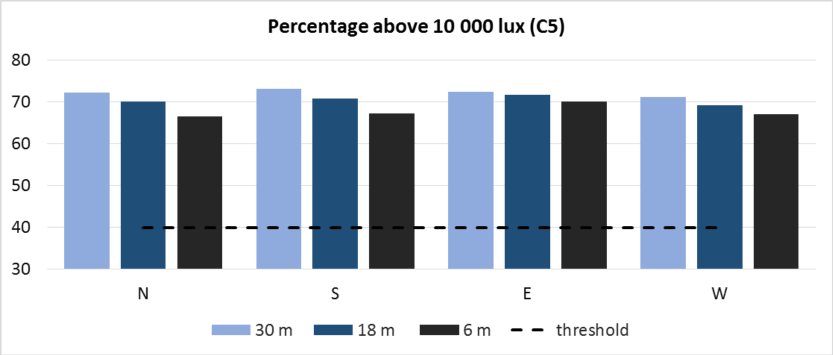
Results (Food)

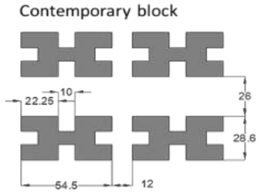
- No facade and typology achieve the threshold requirement (RS=80%). All facades and sensor positions achieve RS > 40%.
- North and south facades show minor differences (N 1-4% higher than S).
- Higher differences were obtained between E & W facades which are more sensitive to sensor height position

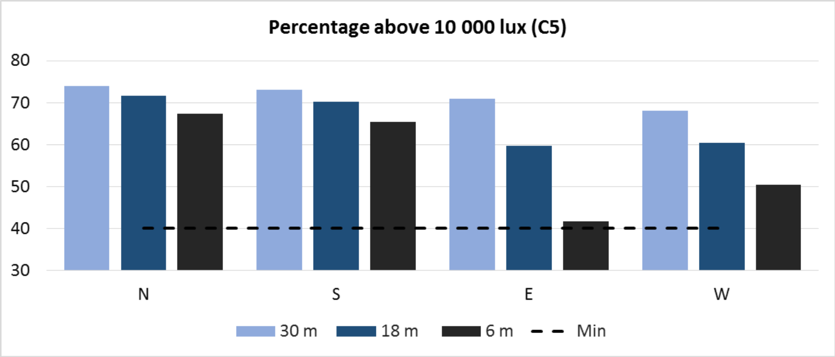






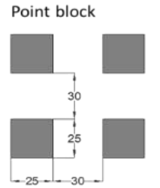


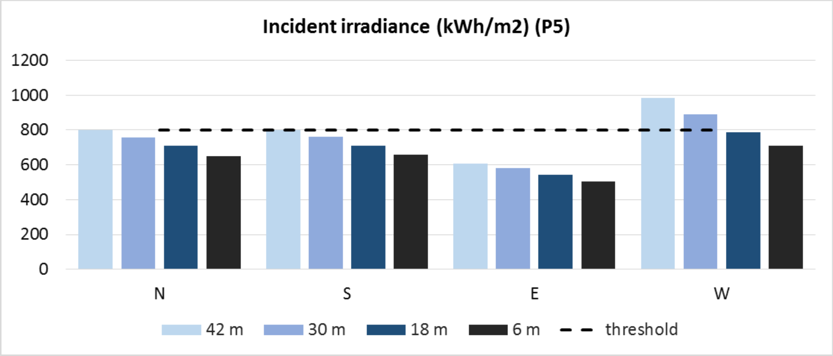


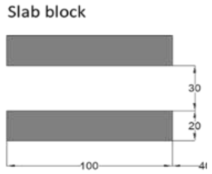


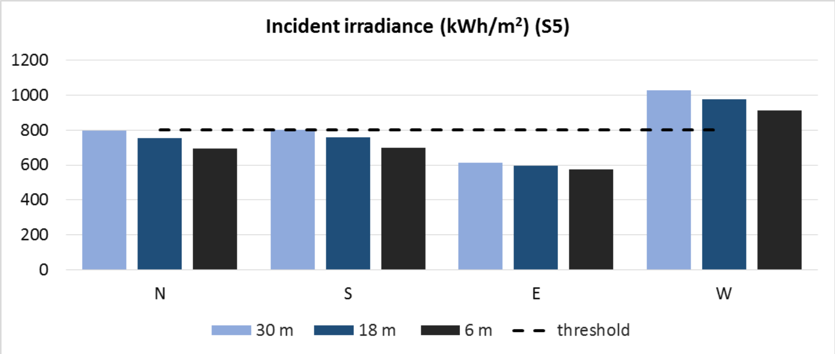
Results (Energy)

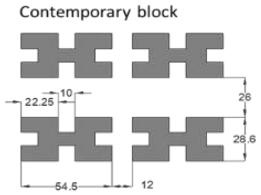
- N & S facades are only suitable on the top positions for the denser cases. It may allow the whole facade for the least dense morphologies (PR = 1.3).
- All cases achieve higher values than 400 kWh/m^2, hence suitable for the installation of solar collectors on those facade locations not suitable for PV panels.

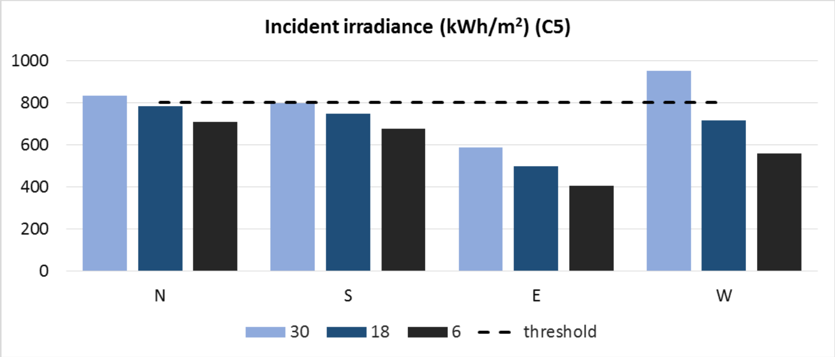












NUS National University of Singapore

Recommendations and partial conclusions

- There is high potential of food and energy harvesting on building facades in low latitudes.

  However, only densities lower than PR=3 allow the incidence of irradiance values above the threshold for energy harvesting

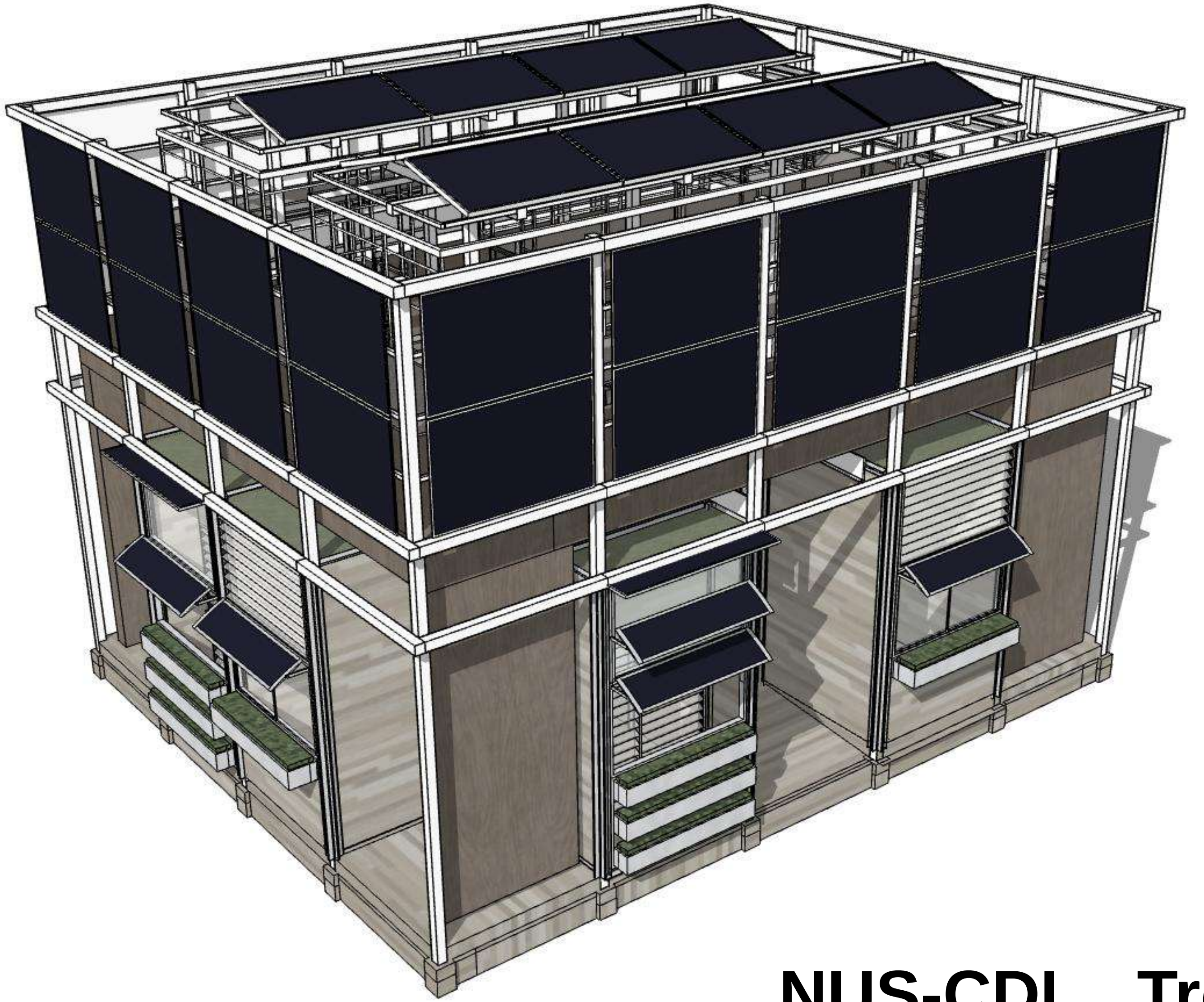
- Farming and solar collectors can be installed on all facades at any height.

  However, it is recommended to be installed only on those facade areas where PV panels are not feasible based on irradiance threshold.

- PV panels on the top section of all facades and farming and solar collectors on the remaining sections.

Cases	Farming 2nd category	PV (>800kWh/m²)				Solar collector
		N	S	E	W	
P1	100%	100%	33%	0%	100%	100%
P3	100%	50%	33%	0%	75%	100%
P5	100%	25%	25%	0%	50%	100%
S1	100%	100%	50%	0%	100%	100%
S3	100%	33%	33%	0%	100%	100%
S5	100%	33%	33%	0%	100%	100%
C1	100%	100%	100%	0%	100%	100%
C3	100%	50%	0%	0%	100%	100%
C5	100%	33%	0%	0%	33%	100%

IV. Productive facades / Design development



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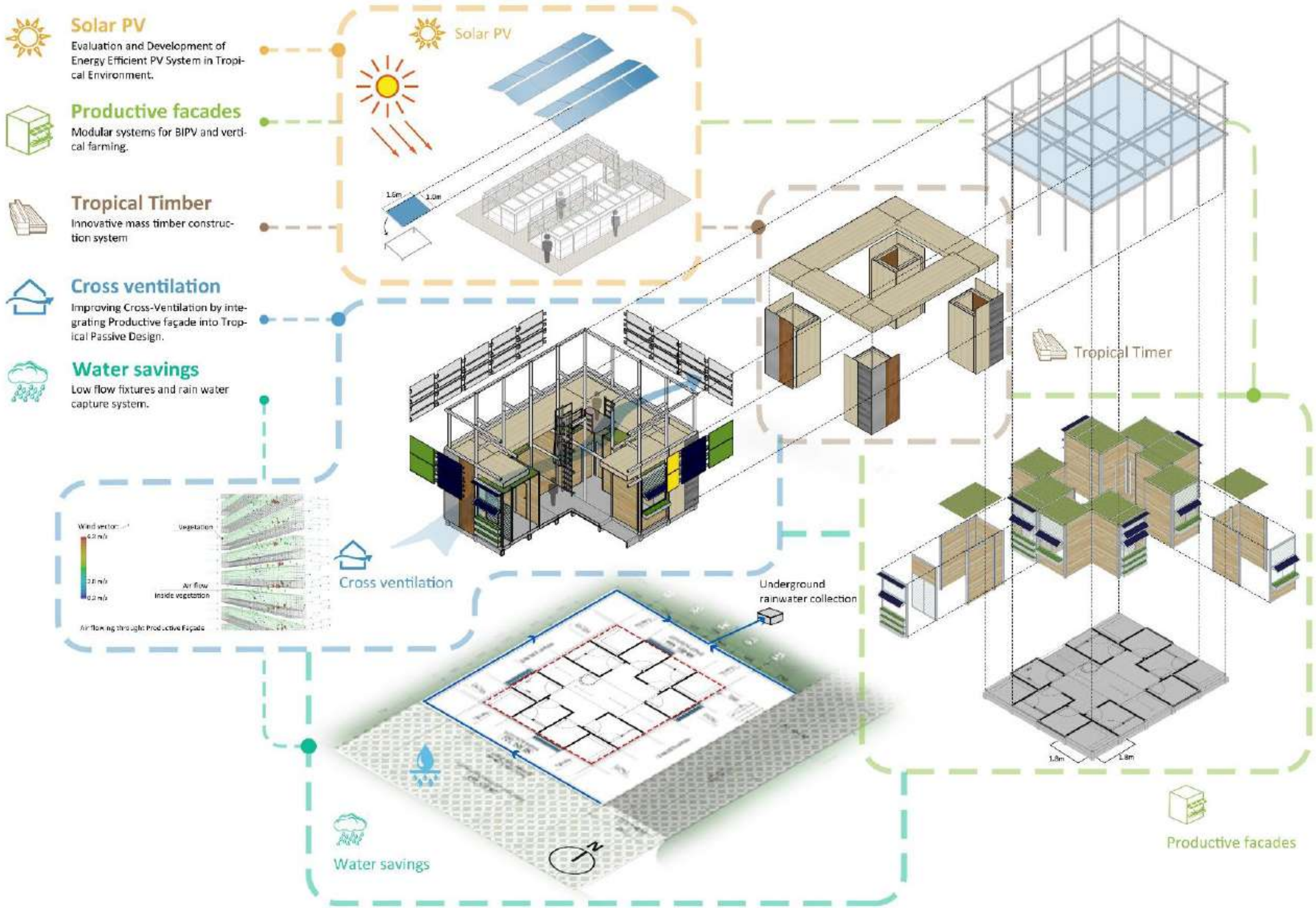
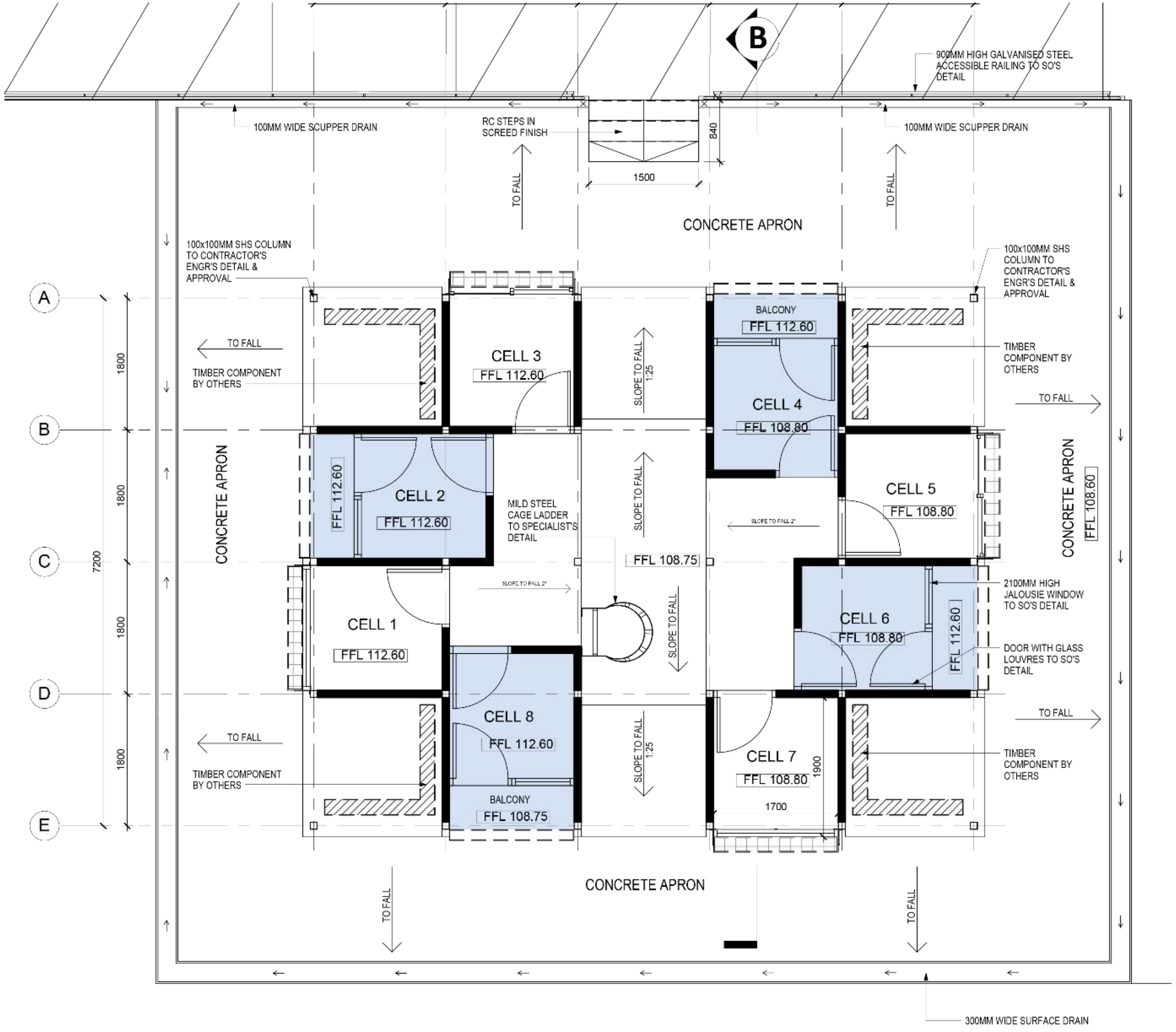
City Development Limited

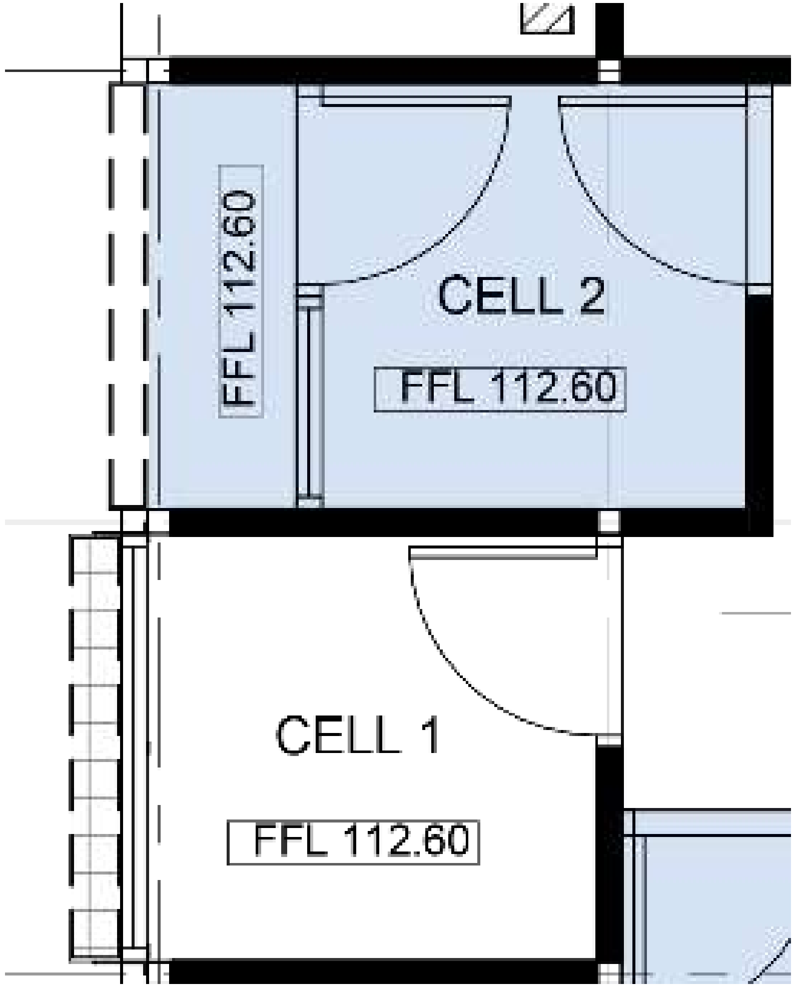
NUS-CDL Tropical Technologies (T^2) Lab

IV. Productive facades / Design development



IV. Productive facades / Design development





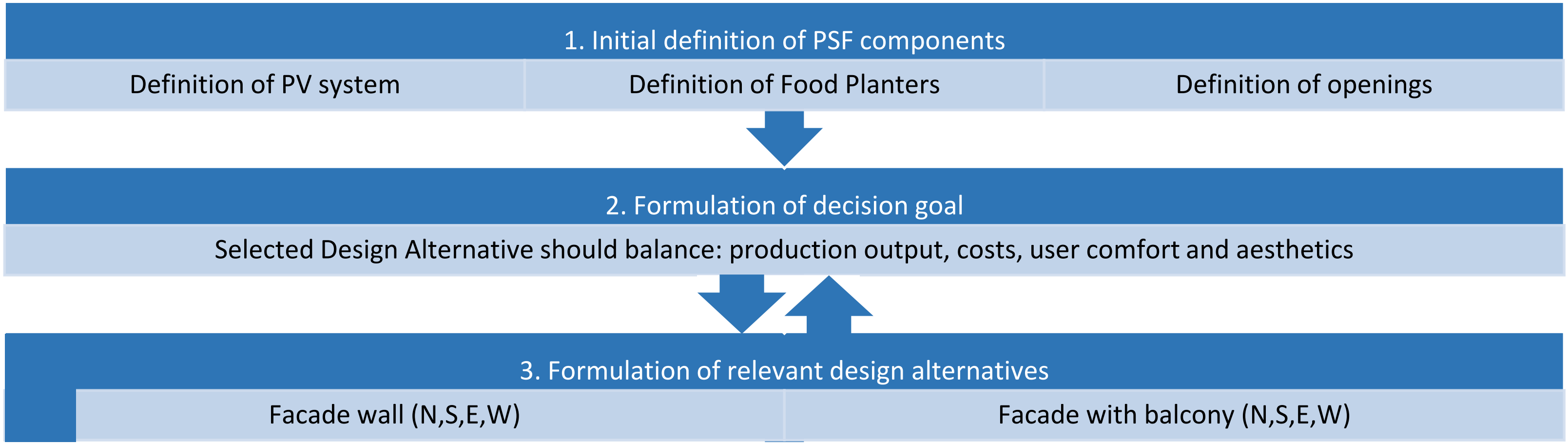
IV. Productive facades / Design development

1. Initial definition of PSF components

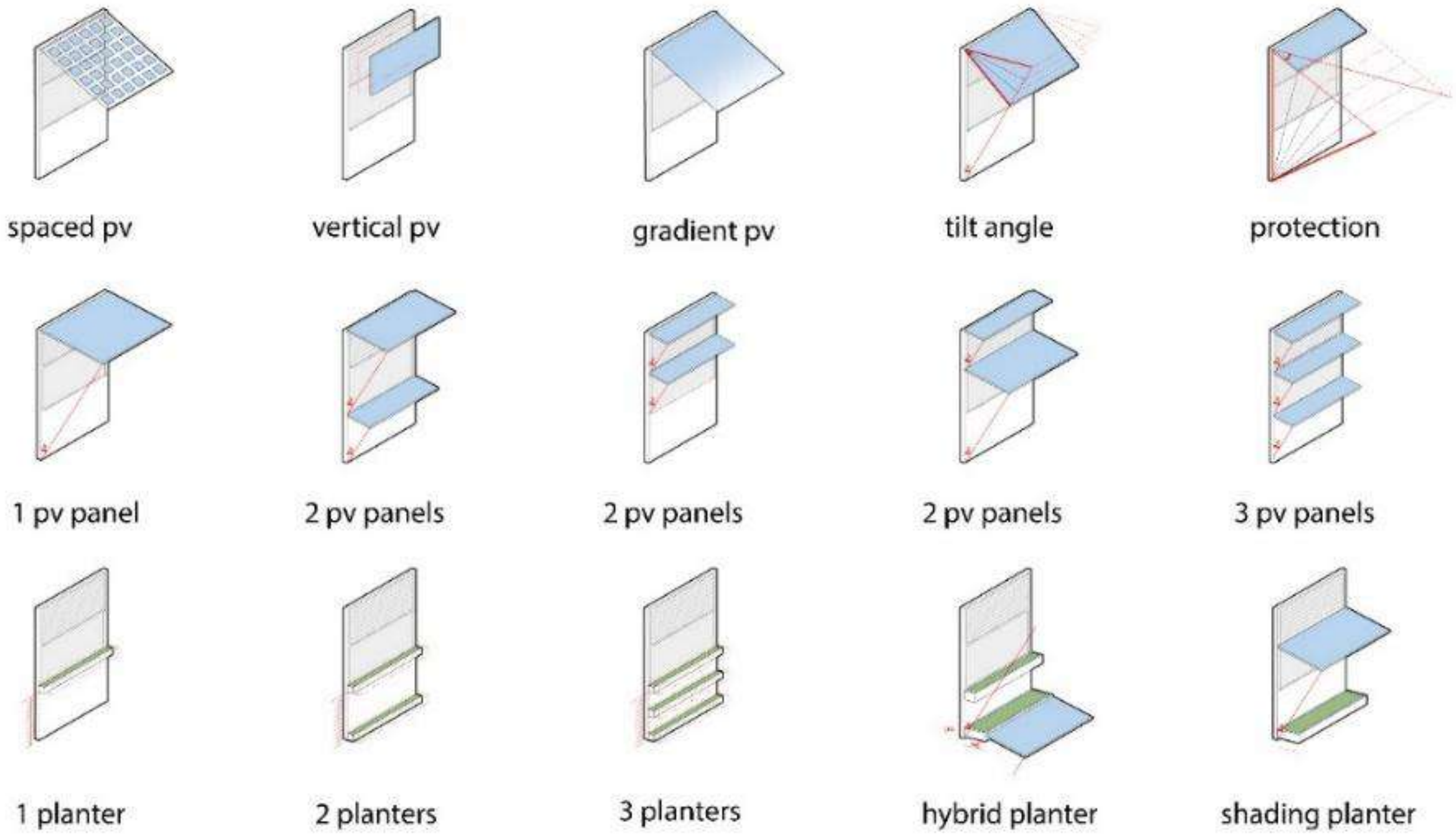
Definition of PV system	Definition of Food Planters	Definition of openings

Crop type		Baseline DLI (for daily survival)	Optimum DLI (for daily growth)	DLI Category	Light Duration Requirement	Spacing	Growing Period	Root Depths	Container	Temperature	Water	Planting Method
Bayam (Chinese spinach or red amaranth)		0.87	33.95	Very high light	Long-day crop Min 4 hour daylight	4/ft2 300mm 200-250mm height	20-25days 4-5weeks 40days	Shallow(450m-600mm.) Usually 1 ft, up to 5ft	Depth: can be less than 30cm 1-gallon or larger container	10-15°C	Keep soil consistently moist throughout the growing season	well-drained, nutrient-rich soil
Cai xin (Chinese flowering cabbage)		0.85	24.51	High light Strong sun		250-300mm h: 100-400mm 100-200mm H: 200-300mm 150-200mm	30-35days 30-50days	within a depth of 120mm	Depth: 150mm-200mm			light sands to clay loams, but prefers fertile, well-drained soils
Chinese cabbage (Napa cabbage)		0.77	17.35	Moderate light Full sun to part shade	Long-day crop produces more leaves, bigger leaves and a higher biomass under long day conditions at least 4 hours of sunlight is ideal	250-300mm	30-35days 8-12wks after sowing	Shallow	Depth: at least 200mm	13-21°C	Needs much water during the whole growth period During head formation, 1 to 1 ½ inches of water per week is needed Frequent light sprinklings with small-bore sprinklers should be used	high yields on sandy loam
Kailan (Chinese kale)		1.5	47.22	Very high light Strong sun		250-300mm H:250-300mm 150-200mm	40-45days 60-70days 8-12weeks 55-60days	Shallow				Rich soil
Kang kong (Water spinach or convolvulus)		0.67	19.9	Full sun or Moderate light	at least 4 hours of sunlight is ideal	150-300mm 200mm H:up to 300mm	18-22days 50-60days 3-4weeks 60days from sowing 2-3week another round harvest	Shallow	at least 8 inches in depth and diameter	20-30°C	needs much more water than most other vegetable crops. For aquatic culture after planting the land is flooded to 3-5 cm in depth and the water is kept flowing continuously. In moist soil culture, irrigation should take place every 1-2 days for high quality shoots if rainfall is low.	grows in water or on moist soil
Lettuce		0.84	14.51	Moderate light Tolerating some shade light shading in warm temperatures well-lit but shaded position	Long-day crop Min 4 hour daylight 3 hour direct sunlight	250-300mm Height: 4-8 in. 10-14 in spacing 18-30 cm	40-45days 40-50days 70-85days 55-70days (from seed) 30days	Shallow(450m-600mm.)	1 gal container can be as shallow as 6 in.	15-22°C cool climate plant	Hydroponic: 20 ± 3.8 L/kg/y Conventional: 250 ± 25 L/kg/y 20-30cm/year Don't allow soil profile to become depleted	Media bed/NFT/DWC
Pak Choy (Chinese chard)		0.83	39.96	Very high light	at least 4 hours of direct sunlight	250-300mm 200mm H:150-450mm	30-35days 45-75days	Shallow	Depth: can be less than 30cm Depth:150-200mm	15-20°C	During head formation, 1 to 1 ½ inches of water per week is needed Frequent light sprinklings with small-bore sprinklers should be used	
Cabbage			6.4-11.2	Partial sun	Long-day crop Day neutral	2/ft2 250-300mm 600–800mm	90-120days 60-90days 45-70days (from transplanting)	Shallow(450m-600mm.) Majority in upper 12 in.	Usually too large for container, but early maturing and dwarf cultivars can be used. Depth: can be less than 30cm One transplant per 5-gallon container. Or with small varieties, one plant per gallon container.	15-25°C (growth stops at >25°C)	380 to 500 mm during the season	Media bed

IV. Productive facades / Design development



Design alternatives



IV. Productive facades / Design development

1. Initial definition of PSF components

Definition of PV system	Definition of Food Planters	Definition of openings

2. Formulation of decision goal

Selected Design Alternative should balance: production output, costs, user comfort and aesthetics

3. Formulation of relevant design alternatives

Facade wall (N,S,E,W)	Facade with balcony (N,S,E,W)

4. Determination of relevant assessment criteria functions and weight coefficients

Quantitative	Qualitative

od/VIKOR

IV. Productive facades / Design development

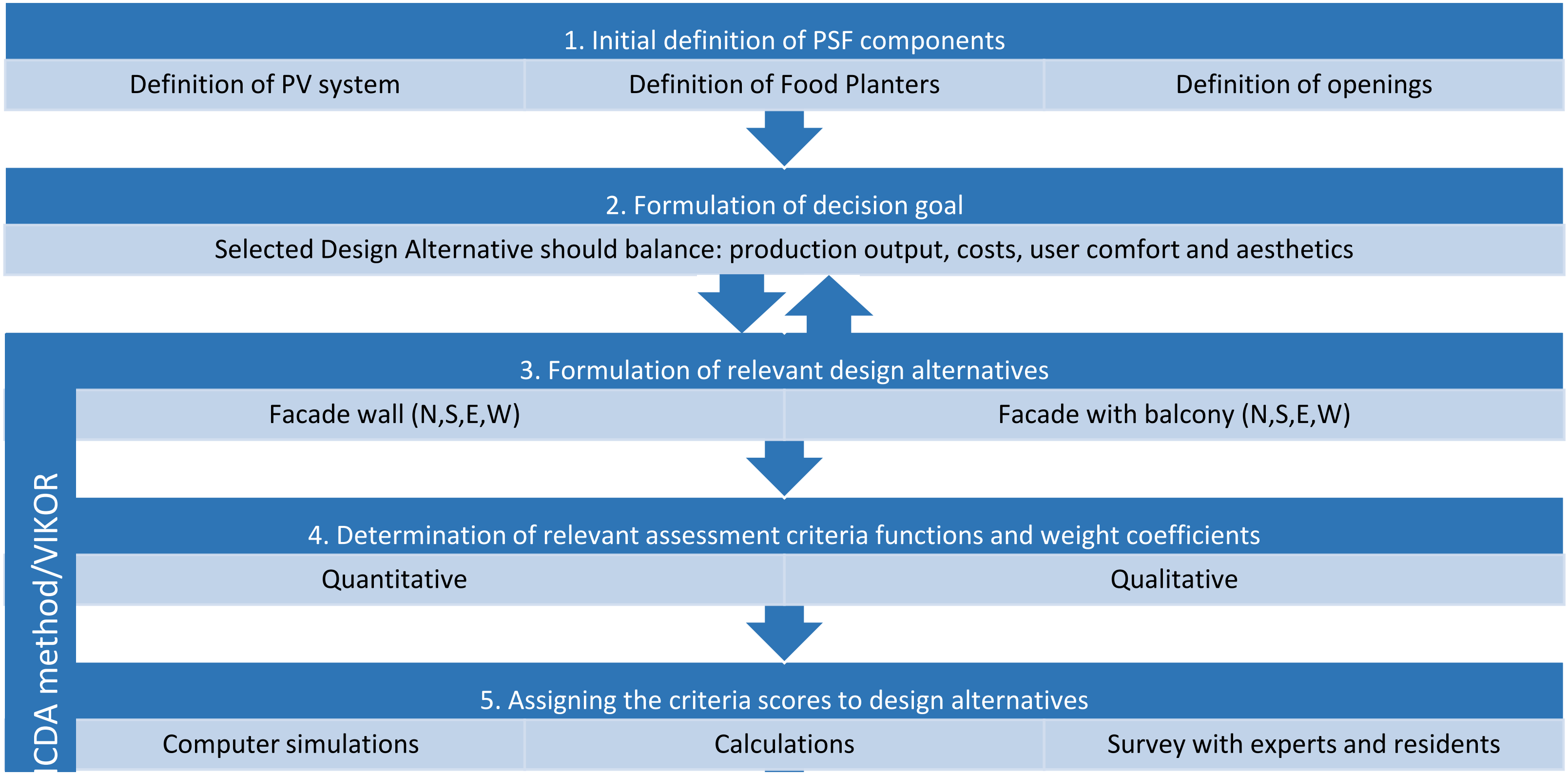
Defining assessment criteria for façade optimization through the multiple criteria decision analysis (MCDA)

The MCDA VIKOR method is applied in order to provide a comprehensive evaluation and selection of the optimal design alternatives.

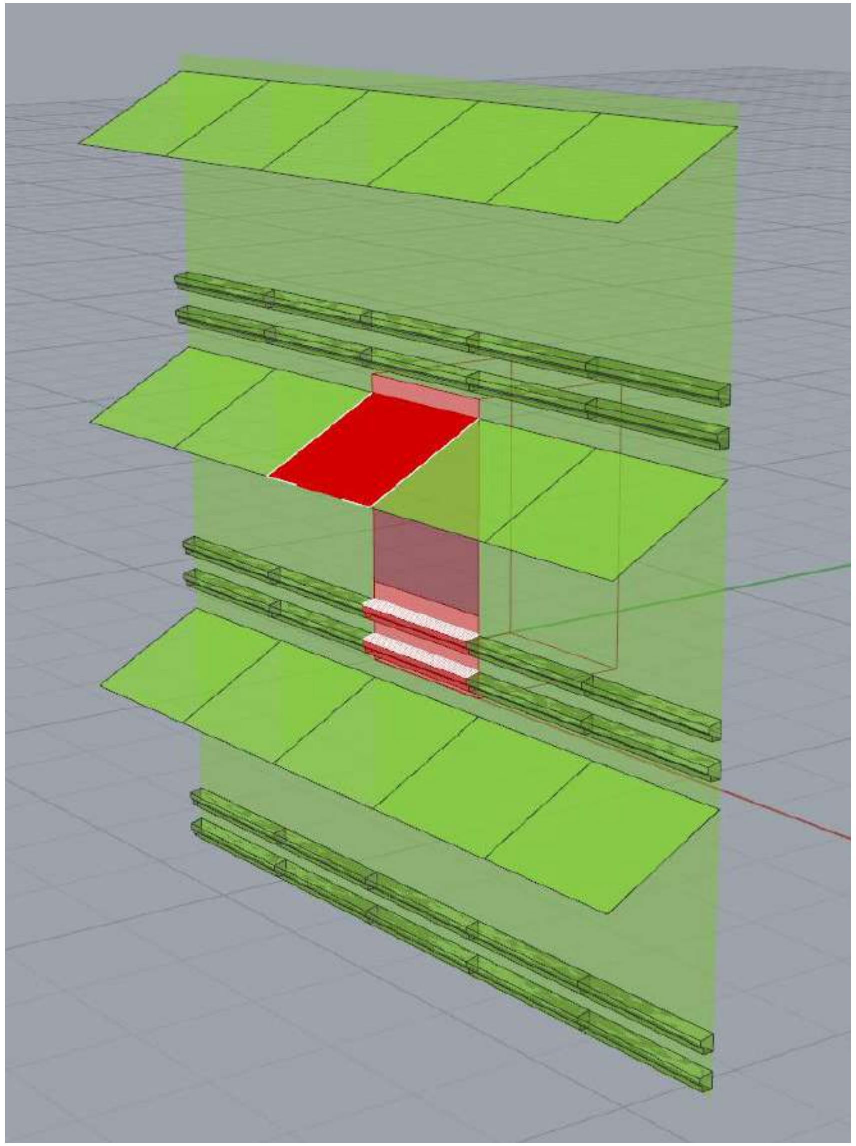
The VIKOR method relies on the weight coefficients of the criteria functions to model the preferred structure of a design strategy.

Criteria categories	Criteria function groups		Individual criteria functions	f_i	Units	ω_i	Ext.
Architectural quality	Functional quality	Daylight performance (0.1)	Daylight Autonomy (indoors)	f_1	%	0.05	Max
			Energy on lighting (indoors)	f_2	KWh	0.05	Min
		Thermal performance (0.1)	Envelope Thermal Transfer Value (ETTV)	f_3	(W/m^2)	0.1	Min
		Natural Ventilation (0.1)	Ventilation rate	f_4	m^3/s	0.05	Max
			Wind speed	f_5	m/s	0.05	Max
		Views quality (0.1)	Angle of view/opening	f_6	degrees	0.1	Max
		Usability & Acceptance (0.1)	Accessibility	f_7	qualitative (1-5)	0.05	Max
			Residents' acceptance	f_8	qualitative (1-5)	0.05	Max
	Aesthetic quality (0.1)		Aesthetic quality of the element	f_9	qualitative (1-5)	0.1	Max
	Constructive quality (0.1)		Components' weight	f_{10}	kg	0.05	Min
			Ease of assembly/disassembly	f_{11}	qualitative (1-5)	0.05	Max
Production performance	Energy yield (0.1)		PV electricity generation per year	f_{12}	KWh	0.1	Max
	Food yield (0.1)		Total value of produced food	f_{13}	SGD	0.1	Max
Financial performance	Costs (0.1)		Installation costs	f_{14}	SGD	0.05	Min
			Maintenance costs per year	f_{15}	SGD	0.05	Min

IV. Productive facades / Design development



IV. Productive facades / Design development



Parametric simulation

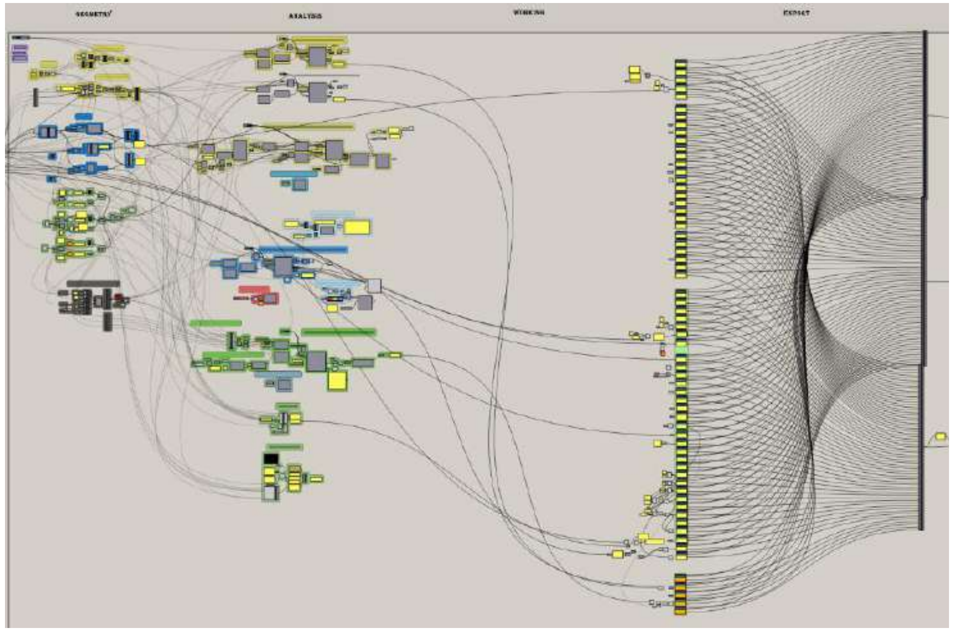
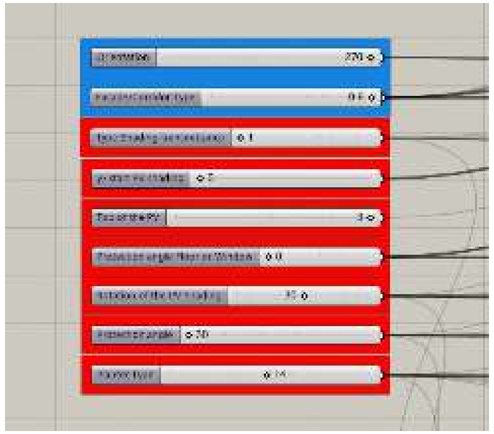


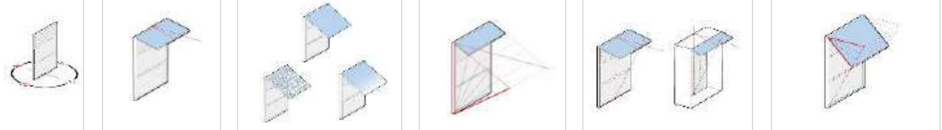
Image of the Rhino model and the Grasshopper / Ladybug algorithm for the parametric calculation of building performance indicators and sunlight access.



IV. Productive facades / Design development

Design variants

2106



Geometric variants | Planter Variants

Orientation		Height of start PV Panel		Opaque		Protection angle		Height of start protection angle		Tilt angle		Geometric variants	Planter Variants
N	1	3.0	1	100%	1	10°	1	bottom height of facade	1	15°			
					2	20°			2	30°	A	1	
					3	30°			3	45°	B	1	
											C	3	
											D	1	
											E	3	
												9	13
												117	

Height bottom window		1 planter		2 planters			3 planters			Height bottom window		1 planter		2 planters	
		M		M	M		M	M	M	900		M		M	M
1100	0	100	3	100	500	6	100	500	900		7	100	10	100	700
	1	500	4	100	900						8	400	11	300	700
	2	900	5	500	900						9	700	12	100	500

Orientation		Height of start PV Panel		Opaque		Protection angle		Height of start protection angle		Tilt angle		Geometric variants	Planter Variants
E	1	3.0	1	100%			1	bottom height of facade	1	15°			
				Transmittant Area of total	1	20°			2	30°	A	1	
			2	50%	2	30°			3	45°	B	3	
				Gradient transmittance	3	40°					C	3	
			3	40%							D	1	
											E	3	
												27	13
												351	

Height bottom window		1 planter		2 planters			3 planters			Height bottom window		1 planter		2 planters	
		M		M	M		M	M	M	900		M		M	M
1100	0	100	3	100	500	6	100	500	900		7	100	10	100	700
	1	500	4	100	900						8	400	11	300	700
	2	900	5	500	900						9	700	12	100	500

Orientation		Height of start PV Panel		Opaque		Protection angle		Height of start protection angle		Tilt angle		Geometric variants	Planter Variants
S	1	3.0	1	100%	1	10°	1	bottom height of facade	1	15°			
					2	20°			2	30°	A	1	
					3	30°			3	45°	B	1	
											C	3	
											D	1	
											E	3	
												9	13
												117	

Height bottom window		1 planter		2 planters			3 planters			Height bottom window		1 planter		2 planters	
		M		M	M		M	M	M	900		M		M	M
1100	0	100	3	100	500	6	100	500	900		7	100	10	100	700
	1	500	4	100	900						8	400	11	300	700
	2	900	5	500	900						9	700	12	100	500

Orientation		Height of start PV Panel		Opaque		Protection angle		Height of start protection angle		Tilt angle		Geometric variants	Planter Variants
W	1	3.0	1	100%			1	bottom height of facade	1	15°			
				Transmittant Area of total	1	20°			2	30°	A	1	
			2	50%	2	30°			3	45°	B	3	
				Gradient transmittance	3	40°					C	3	
			3	40%							D	1	
											E	3	
												27	13
												351	

Height bottom window		1 planter		2 planters			3 planters			Height bottom window		1 planter		2 planters	
		M		M	M		M	M	M	900		M		M	M
1100	0	100	3	100	500	6	100	500	900		7	100	10	100	700
	1	500	4	100	900						8	400	11	300	700
	2	900	5	500	900						9	700	12	100	500

Orientation		Height of start PV Panel		Opaque		Protection angle		Height of start protection angle		Tilt angle		Geometric variants	Planter Variants
N	1	3.0	1	100%	1	no pv	1	bottom height of facade	1	15°			
					2	20°			2	30°	A	1	
					3	30°			3	45°	B	1	
											C	3	
											D	1	
											E	3	
												9	13
												117	

Height bottom window		1 planter		2 planters			3 planters			Height bottom window		1 planter		2 planters	
		M		M	M		M	M	M	900		M		M	M
1100	0	100	3	100	500	6	100	500	900		7	100	10	100	700
	1	500	4	100	900						8	400	11	300	700
	2	900	5	500	900						9	700	12	100	500

Orientation		Height of start PV Panel		Opaque		Protection angle		Height of start protection angle		Tilt angle		Geometric variants	Planter Variants
E	1	3.0	1	100%			1	bottom height of facade	1	15°			
				Transmittant Area of total	1	20°			2	30°	A	1	
			2	50%	2	30°			3	45°	B	3	
				Gradient transmittance	3	40°					C	4	
			3	40%	4	50°					D	1	
											E	3	
												36	13
												468	

Height bottom window		1 planter		2 planters			3 planters			Height bottom window		1 planter		2 planters	
		M		M	M		M	M	M	900		M		M	M
1100	0	100	3	100	500	6	100	500	900		7	100	10	100	700
	1	500	4	100	900						8	400	11	300	700
	2	900	5	500	900						9	700	12	100	500

Orientation		Height of start PV Panel		Opaque		Protection angle		Height of start protection angle		Tilt angle		Geometric variants	Planter Variants
S	1	3.0	1	100%	1	no pv	1	bottom height of facade	1	15°			
					2	20°			2	30°	A	1	
					3	30°			3	45°	B	1	
											C	3	
											D	1	
											E	3	
												9	13
												117	

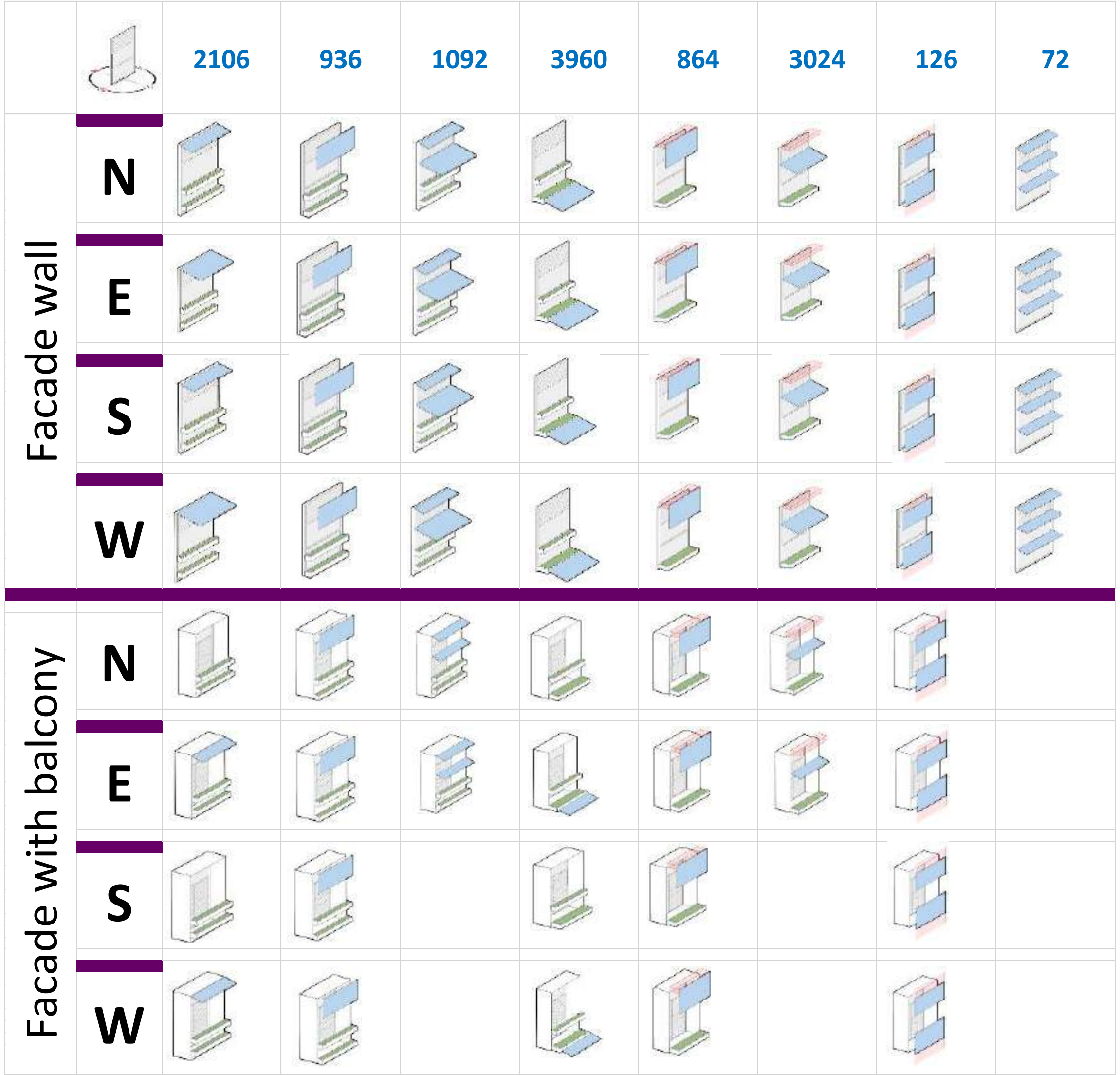
Height bottom window		1 planter		2 planters			3 planters			Height bottom window		1 planter		2 planters	
		M		M	M		M	M	M	900		M		M	M
1100	0	100	3	100	500	6	100	500	900		7	100	10	100	700
	1	500	4	100	900						8	400	11	300	700
	2	900	5	500	900						9	700	12	100	500

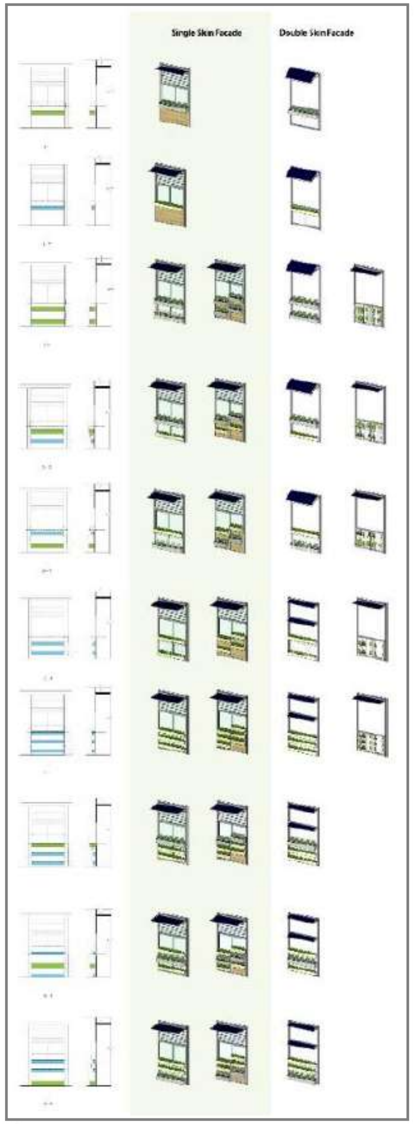
Orientation		Height of start PV Panel		Opaque		Protection angle		Height of start protection angle		Tilt angle		Geometric variants	Planter Variants
W	1	3.0	1	100%			1	bottom height of facade	1	15°			
				Transmittant Area of total	1	20°			2	30°	A	1	
			2	50%	2	30°			3	45°	B	3	
				Gradient transmittance	3	40°					C	4	
			3	40%	4	50°					D	1	
											E	3	
												36	13
												468	

Height bottom window		1 planter		2 planters			3 planters			Height bottom window		1 planter		2 planters	
		M		M	M		M	M	M	900		M		M	M
1100	0	100	3	100	500	6	100	500	900		7	100	10	100	700
	1	500	4	100	900						8	400	11	300	700
	2	900	5	500	900						9	700	12	100	500

IV. Productive facades / Design development

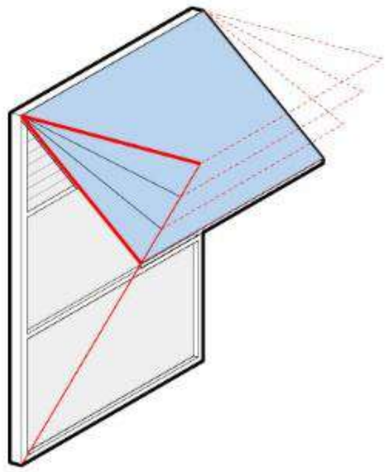
Design variants (total 12,180)

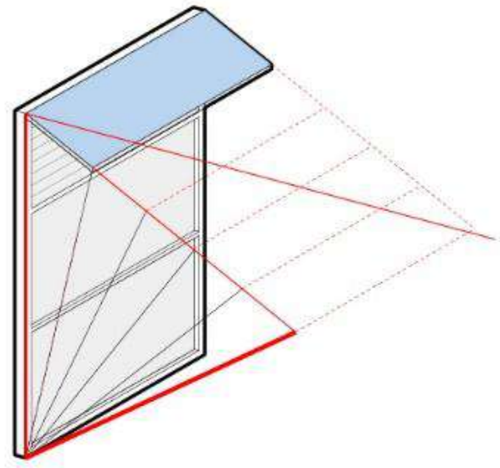


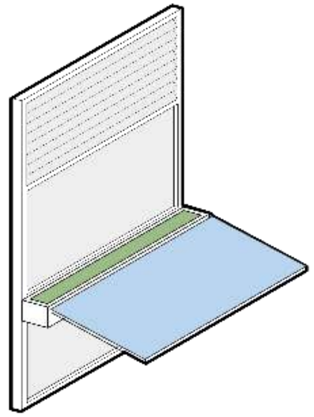


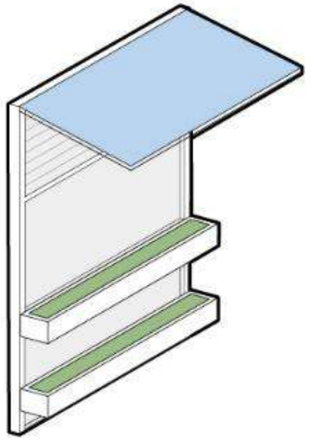
IV. Productive facades / Design development

Example: Test-run of the simulation









Tilt angle
15/30/45

Protection angle
10/20/30

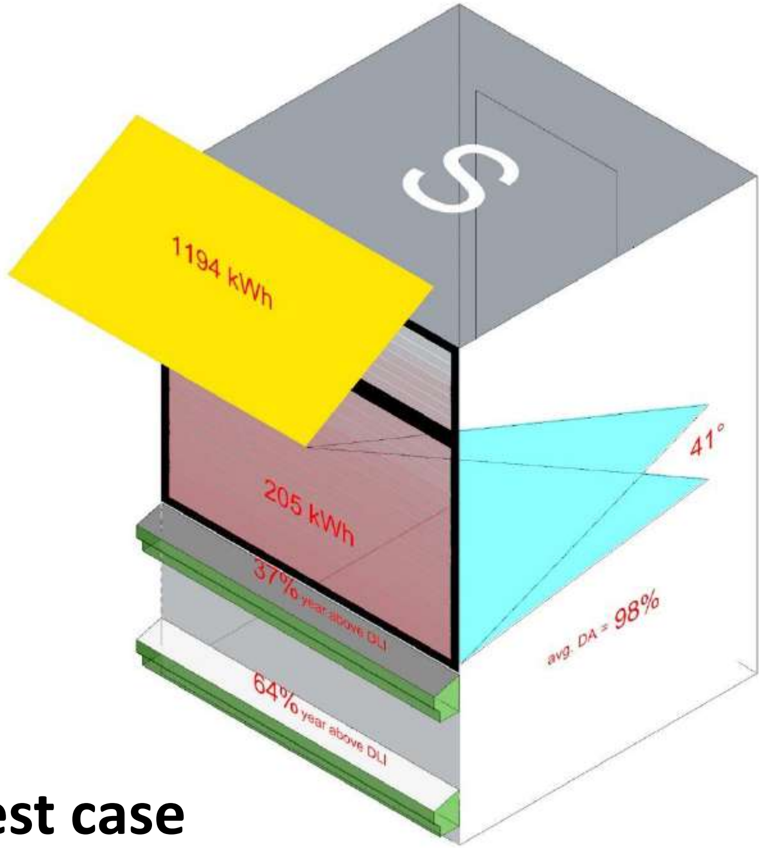
Start PV shading
Top facade/planter

Planter
configuration

3 x 3 x 2 x 13

234 Cases

Simulation results



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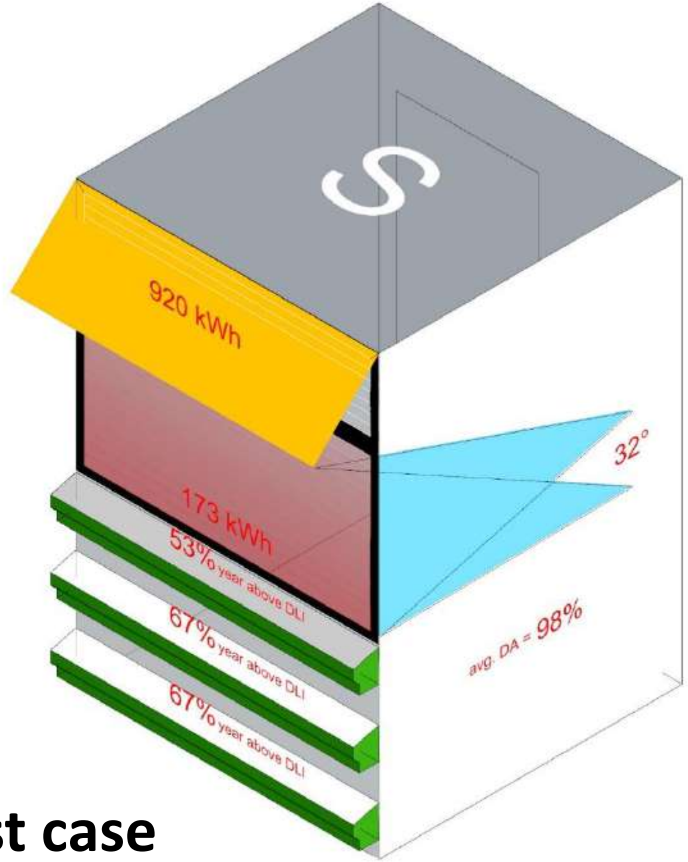

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Best case

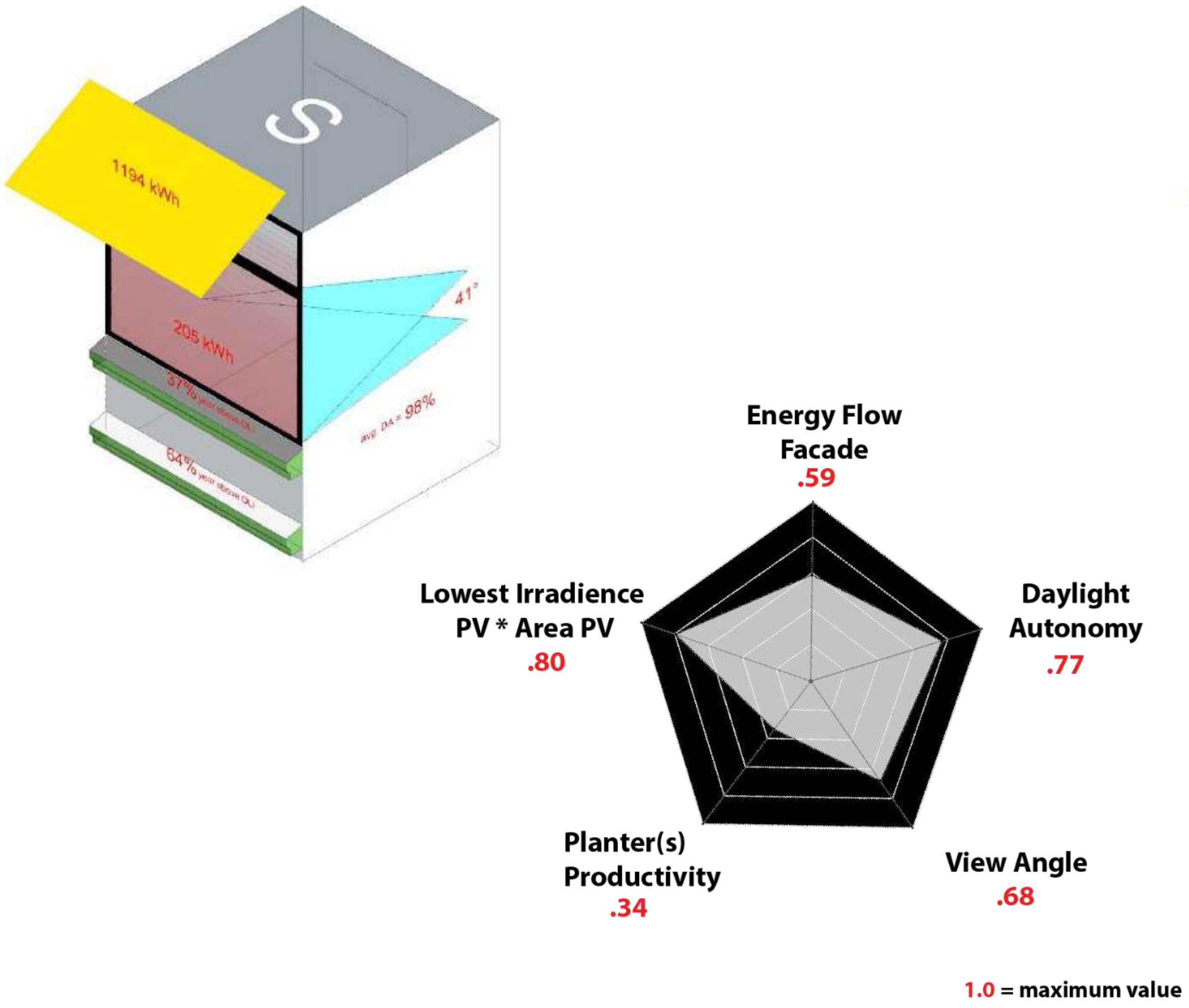
Prot. angle (20°) Tilt angle (30°)
Start shading (planter) Planter type (a10)

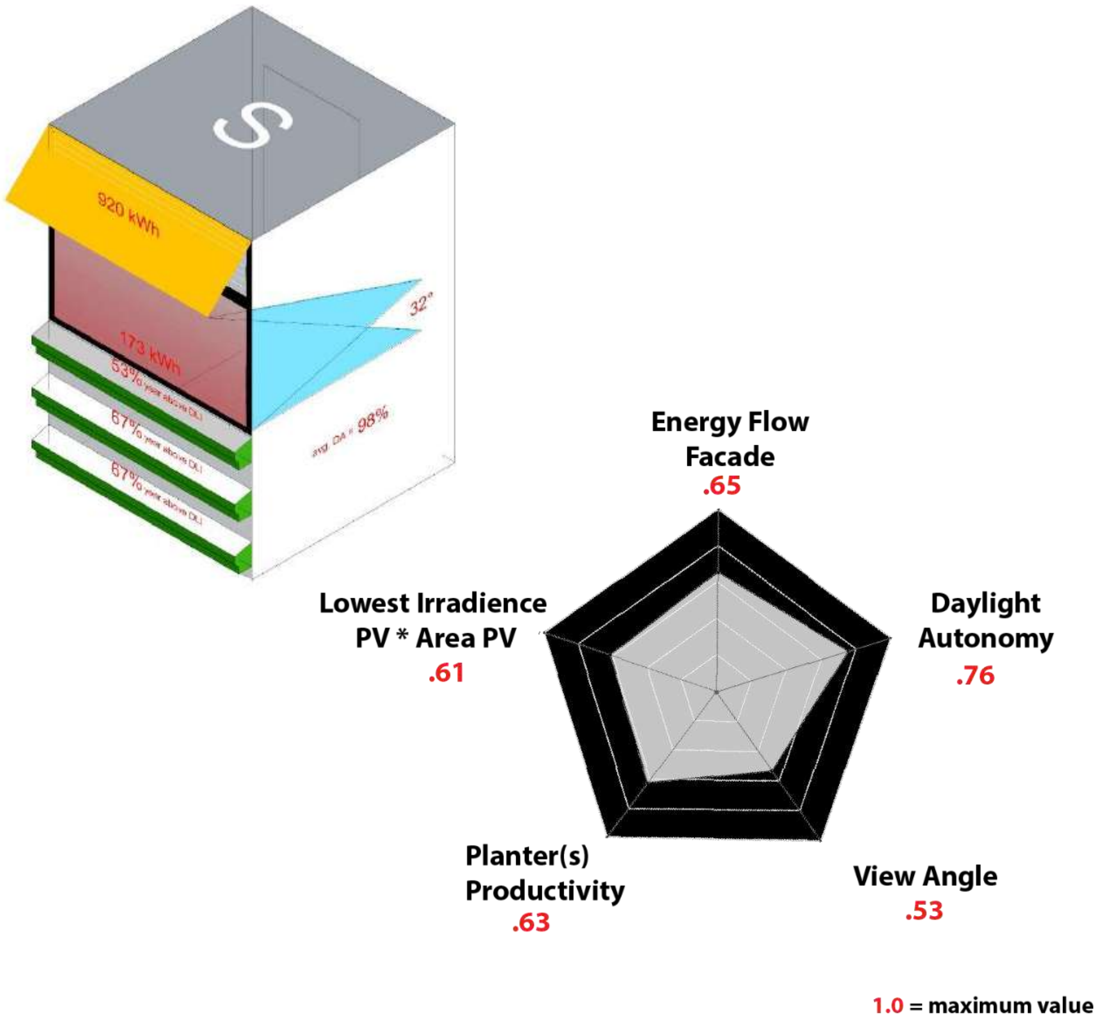
Second best case

Prot. angle (10°) Tilt angle (45°)
Start shading (top fac.) Planter type (a6)

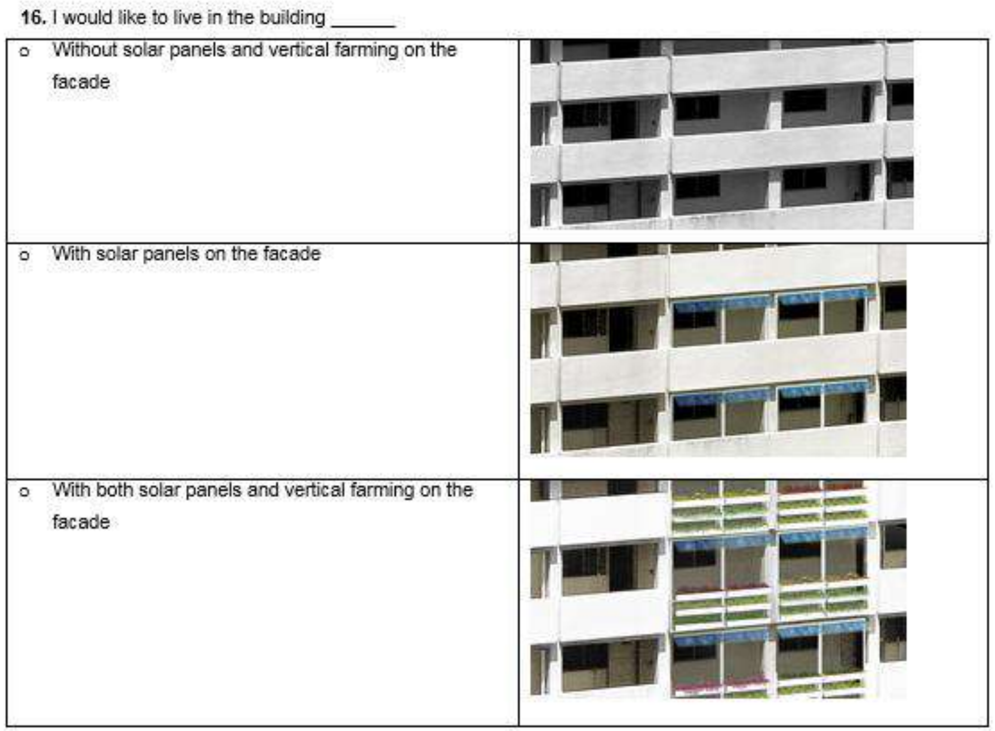
IV. Productive facades / Design development

Simulation results



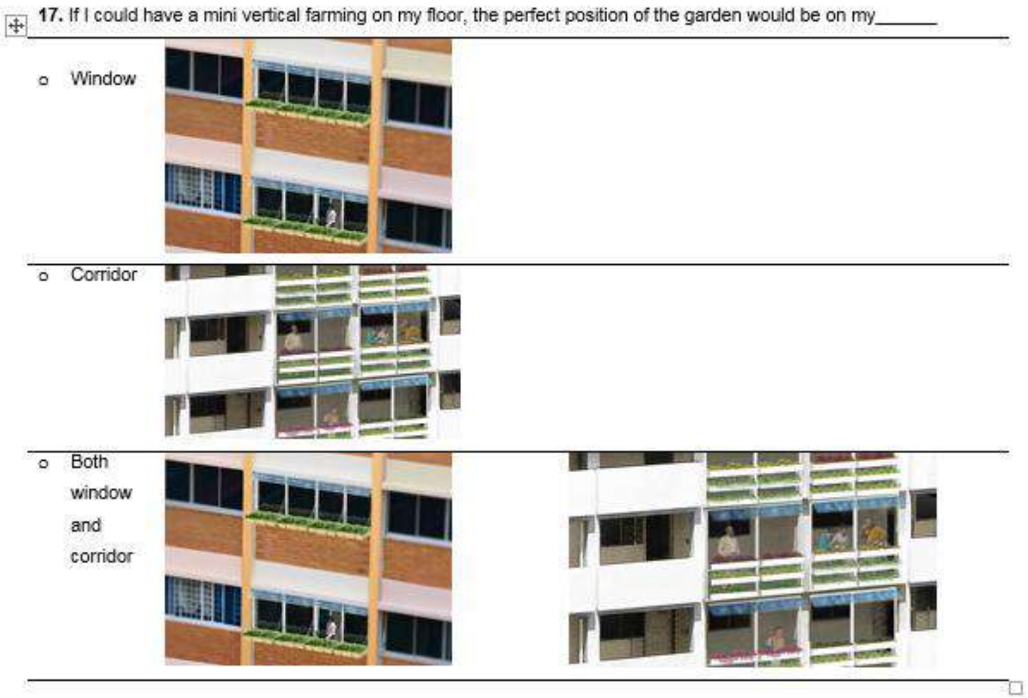


Survey to residents and experts



16. I would like to live in the building ______

- Without solar panels and vertical farming on the facade
- With solar panels on the facade
- With both solar panels and vertical farming on the facade



17. If I could have a mini vertical farming on my floor, the perfect position of the garden would be on my______

- Window
- Corridor
- Both window and corridor

Extract of the survey to be conducted to residents of HDB buildings in order to obtain some of the criteria functions related to acceptance, accessibility and aesthetics.

IV. Productive facades / Design development

1. Initial definition of PSF components

Definition of PV system	Definition of Food Planters	Definition of openings

2. Formulation of decision goal

Selected Design Alternative should balance: production output, costs, user comfort and aesthetics

MCDA method/VIKOR

3. Formulation of relevant design alternatives

Facade wall (N,S,E,W)	Facade with balcony (N,S,E,W)

4. Determination of relevant assessment criteria functions and weight coefficients

Quantitative	Qualitative

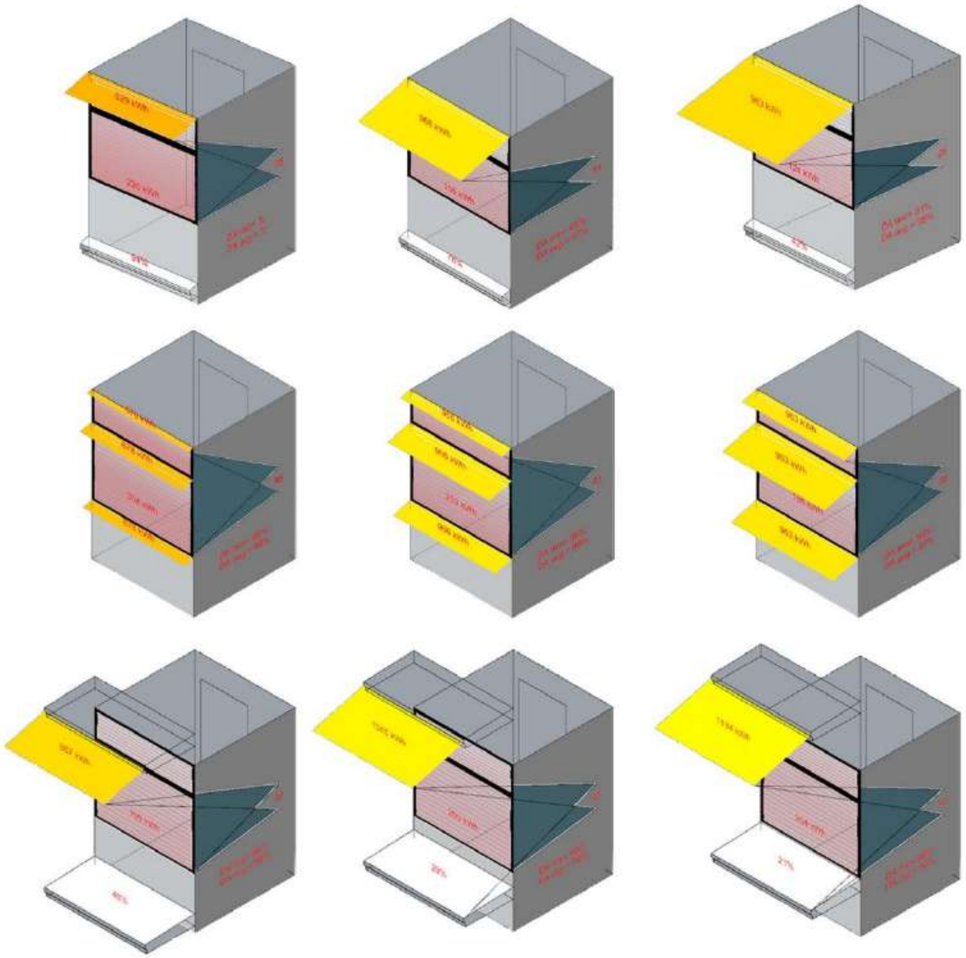
5. Assigning the criteria scores to design alternatives

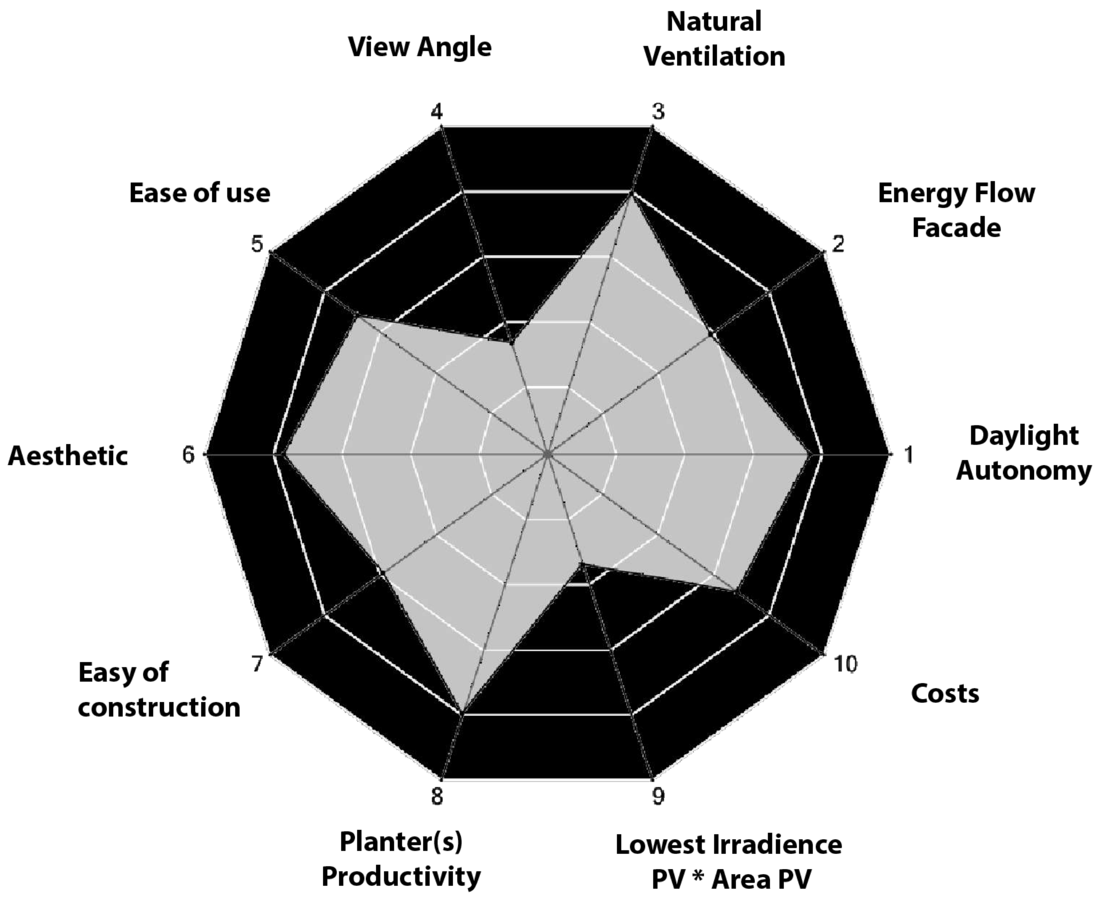
Computer simulations	Calculations	Survey with experts and residents

6. Evaluation of SPF design alternatives and selection of the optimal SPF design alternative

Accepting one Design: proceed to step 7	Not accepting design: return to any previous step

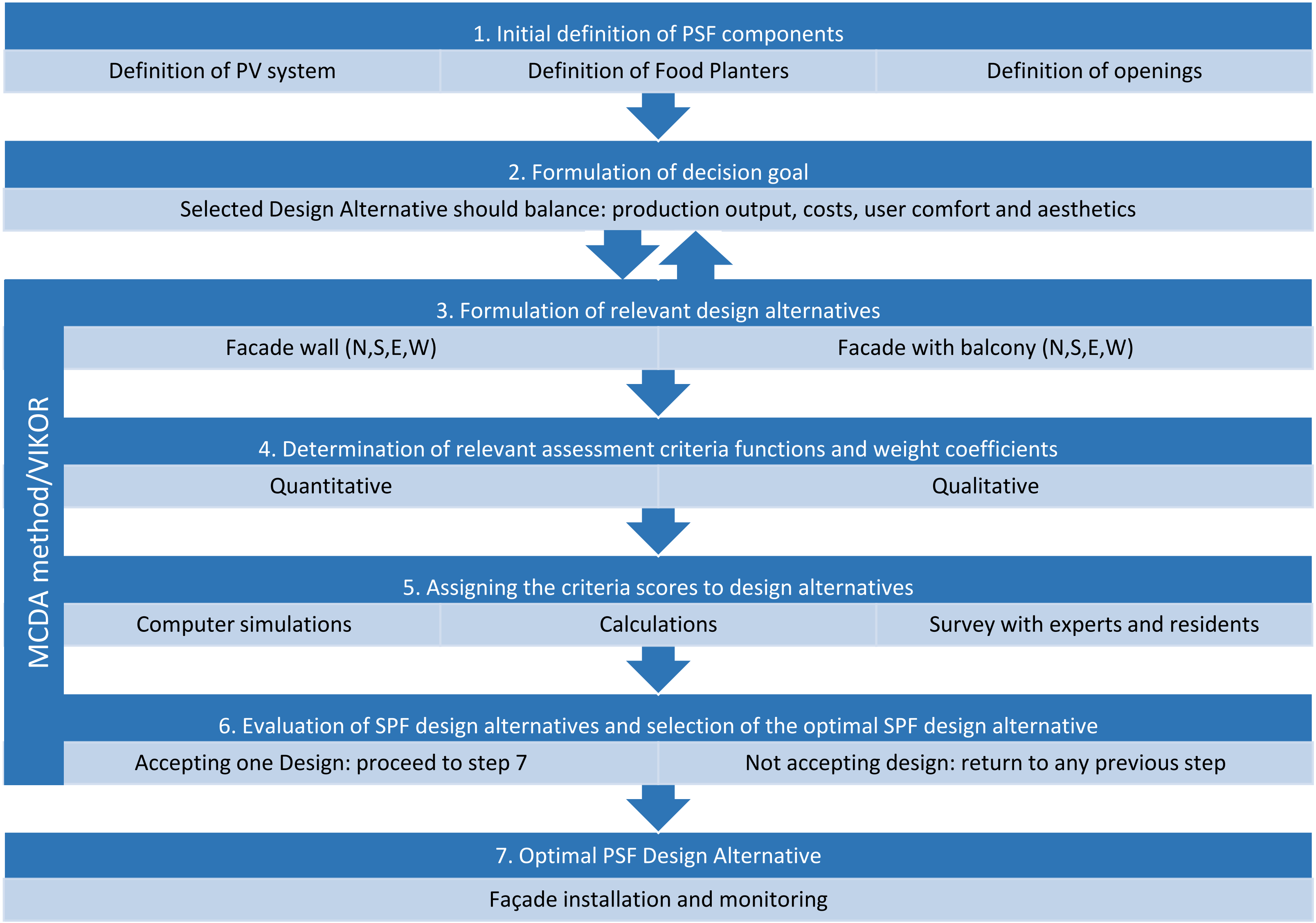
VIKOR: multiple criteria decision analysis (MCDA)





IV. Productive facades / Design development

IV. Productive facades / Design development



Experiment results: to be reported next time!

Thank you very much
Questions and suggestions
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